Directed Energy and Fleet Defense

Implications for Naval Warfare

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May 2000

10

Occasional Paper No. 10
Center for Strategy and Technology
Air War College

Air University
Maxwell Air Force Base

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Directed Energy and Fleet Defense: Implications for Naval Warfare**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **William J. /McCarthy**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air University Press Maxwell AFB, AL 36112-6615**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**88**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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Occasional Paper No. 10
Center for Strategy and Technology
Air War College

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Maxwell Air Force Base, Alabama 36112

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The Author

William J. McCarthy, Captain, USN, is a 1976 graduate of the College of the Holy Cross. Designated as a Naval Flight Officer, he spent the majority of his career flying the E-2C Hawkeye. Operational flying tours included VAW-125, VAW-121 and VAW-126. While serving as Executive Officer of VAW-126, he participated in Operation Desert Shield and Operation Desert Storm, flying more than thirty combat missions. He assumed command of VAW-126 in December 1991. Under his command, the Seahawks deployed on the USS *John F. Kennedy* in support of Operation Provide Promise and Adriatic operations. Following command, he served on the staff of Commander, Carrier Group Four. In July 1993, he was selected for Navy Nuclear Power Training. Upon completion of training, he reported as Prospective Executive Officer, *John C. Stennis*, in October 1995. Following the ship's commissioning, he served as Executive Officer until December 1996. In January 1997, he assumed command of the Fast Combat Support Ship, *USS Detroit*, completing a successful Mediterranean and Arabian Gulf deployment and a $24 million dollar shipyard availability. A distinguished graduate of the U.S. Naval Test Pilot School, his shore duty assignments included the Naval Air Test Center where he served as the Project Officer for the E-2C APS-138 Radar and Update Development Programs, and he later joined the USNTPS faculty as the Senior Airborne Systems Instructor. Assigned to Naval Air Systems Command Headquarters, he served as the E-2C Avionics Systems Project Officer. He has flown over thirty different military aircraft, accumulating over 4,000 hours and 700 arrested landings. A 1999 graduate of the Air War College, this research was conducted under the auspices of the Center for Strategy and Technology. His current assignment is the commander of the Nimitz-class nuclear powered aircraft carrier, the *USS George Washington*.

Preface

I am indebted to many individuals who contributed their time and knowledge to this study. In particular, I would like to acknowledge Patrick Vail of the Air Force Research Laboratory at the Phillips Research Site, and Joung R. Cook of the US Naval Research Laboratory, who provided useful information and insights. I also want like to express my sincerest thanks to my colleagues at the Center for Strategy and Technology, in particular Joe Shirey and Eileen Walling, who have shared my commitment to raising interest in directed energy warfare. My Air War College faculty advisors, Dr. William Martel and Col (Ret) Theodore Hailes, gave me invaluable encouragement and editorial assistance. Air War College faculty members Grant Hammond and Dan Hughes also provided helpful insights into modern strategic thought. Finally, my deepest thanks and appreciation go to my ever-patient family, my wife, Sharon, and our daughter Katie. That being said, I alone am responsible for the contents of this study.

Abstract

The introduction of directed energy weapons into twenty-first century naval forces has the potential to change naval tactics as fundamentally as the transition from sail to steam. Recent advances in directed energy technologies have made the development of both high-energy laser and high-power microwave weapons technically feasible. This study examines the potential adaptation of such weapons for the defense of naval forces.

This study considers options for using directed energy systems on naval vessels in the context of the U.S. maritime strategy and emerging threats in international politics. The framework for this study is an integrated system of microwave devices, high-energy lasers, and surface-to-air missiles which are evaluated in terms of their ability to enhance anti-ship cruise missile defense, tactical air defense, and fast patrol boat defense. This study also examines collateral capabilities, such as non-lethal defensive measures and counter-surveillance operations.

The global proliferation of increasingly sophisticated weapons and the expanding demands placed on its ever-smaller navy require the United States to reassess its current approach to fleet operations. This study concludes that directed energy technology has made sufficient progress to warrant the development of sea-based weapons systems for deployment in the first two decades of the next century. For operational and technical reasons, a Nimitz class aircraft carrier may be the preferred platform for the initial implementation of directed energy weapons. If successful, the robust self-defense capability provided by directed energy weapons will permit a fundamental shift in carrier battle group operations from a massed, attrition oriented defense to a more dynamic, dispersed offense.

I. Introduction

Technological innovation in the latter half of the twentieth century has fueled a revolution in military affairs. While much has been written concerning the emergence of the information age and the role of information warfare, it is important to consider that less thought has been given to the technologies of warfare that operate at the speed of light.[1] This gap is unfortunate, as the introduction of directed energy weapons has the potential to change naval warfare as fundamentally as the transition from sail to steam.

As articulated in 1997 in its *Forward ... From the Sea*, the United States Navy is committed to waging expeditionary warfare in full partnership with the Marine Corps. Fleet defense will need to respond to threats that may include low observable or hypersonic cruise missiles, tactical ballistic missiles with maneuverable re-entry vehicles, space-based surveillance systems, fast missile patrol boats, advanced submarines, and ultimately, weapons of mass destruction. To this list, it may be necessary to add airborne or space based lasers, as well as explosively driven directed energy weapons.

Over the last forty years, the United States defense establishment has developed directed energy technology with a vigor that has waxed and waned with technological triumphs and unresolved challenges. The capability to use directed energy systems for the destruction of airborne targets was demonstrated over 20 years ago; yet today, the utility of directed energy systems continues to be debated. Born under the shadow of the inter-continental ballistic "missile gap," directed energy weapons, and lasers in particular, were offered as a possible alternative to reduce the nation's vulnerability. In the mid-1980's, the Strategic Defense Initiative provided another major infusion of resources. But as the enthusiasm for "Star Wars" ebbed, military investment again declined.

In a profound way, the Gulf War dispelled many of the doubts that surrounded the U.S. military's embrace of technology. Predictions that sophisticated weapons and sensors would prove impractical in actual combat were shown to be incorrect. This sparked another renaissance in directed energy research. Two years ago, the U.S. Air Force study of air and space warfare in the twenty-first century known, as *New World Vistas*, devoted an entire volume to directed energy.[2] On the other hand, the 1997 study *Technology for the United States Navy and Marine Corps, 2000-2035* conducted by the National Academy of Science, was not sanguine about the feasibility of using directed energy for defensive systems.[3]

The pessimism expressed in some quarters may be due, in part, to the excessive optimism expressed in earlier decades, as generations of technologists promised that a revolutionary weapon was just around the corner.[4] Anticipating that lasers would be adapted at the same pace as the development of the airplane, both scientists and military leaders were disappointed.[5] Regardless of one's perspective, these and other studies raise serious issues that merit close examination by the defense establishment.

The purpose of this study is to examine the current state of developments in the field of directed energy weapons in order to assess the potential value of such systems for defending naval fleets, which is known as "fleet defense." Since the military and, particularly, naval forces of the first two decades of the next century will be the product of the technologies that are produced today, it is appropriate to focus this study on the years 2020-2025. The timing is fortuitous because it corresponds with the predicted refuelings of the *Nimitz* class aircraft carriers USS *John C. Stennis* and USS *Harry S. Truman*. The mid-life re-fueling of a nuclear powered aircraft carrier is a multi-billion dollar investment.[6] To be affordable or at least economically efficient, any major changes in naval combat systems must be accomplished as part of that overhaul. This is clearly a once in a lifetime opportunity in the fifty-year or greater service life of an aircraft carrier. One conclusion of this study is that the United States must identify and develop the critical technologies that are needed to support these changes and do to so as rapidly as possible.

This study examines the Navy's strategic concepts for the next century and assesses the likely threats that the United States could encounter. It then reviews the utility of alternative weapons, notably high-energy lasers and radio frequency (RF) weapons, which are the principal directed energy weapon concepts examined in this study. Given the significant technical differences, each technology is discussed separately. The feasibility of implementing one or more of these technologies in a Nimitz class carrier is then examined.

The challenge facing the Navy today is similar to the predicament that it faced in the 1950's when experiments showed that, while submarine launched cruise missiles were feasible there was no effective targeting scheme for employing them. The result was a thirty year delay in fielding the submarine launched cruise missile, which is one of the more capable weapons today. As noted by modern strategists, the Navy was indeed fortunate that the development of large caliber guns was not delayed until Admiral William S. Sims developed an effective fire control system.[7] However,

the counterpoint was well articulated when Bernard Brodie observed that "men who have been condemned out of hand as unimaginative or unprogressive may simply have been much more acutely aware of technical difficulties to overcome before a certain invention could be useful than were their more optimistic contemporaries."[8]

The balance of this study is devoted to assessing the implications of directed energy technologies for fleet defense and supporting the strategic missions of U.S. naval forces. The potential capabilities of these systems are examined in terms of classical and modern strategic thought, with particular emphasis on the challenges of employing naval power to influence nations whose naval forces are designed to contest rather than to control the sea.

The implementation of a major new class of weapons has historically led to new concepts for naval force employment. These tactics must be developed iteratively, just as the weapons themselves. New tactics and new technology will likely lead to new issues, including the evolution of countermeasures as well as the development of entirely new concepts. A prominent example of the latter is whether laser systems on naval vessels could be used as anti-satellite weapons.

Ultimately, the goal of this study is to establish a framework for understanding whether the U.S. Navy should pursue the near-term development of either or both directed energy technologies for incorporation in its aircraft carrier force. Given that other nations are making the investment to develop and field directed energy weapons, now is the time to make a commitment if the United States is to achieve an initial operational capability by the end of the first quarter of the twenty-first century.[9] For these reasons, it is imperative for naval thinkers to examine the capabilities, limitations, and military utility of "speed of light" weapons. As the most information-dependent combat force in the world, the United States has no choice but to understand how these emerging technologies will influence national security.

II. U. S. Navy Strategic Concepts

The Navy's strategic concept outlined in *Forward ... From the Sea* defines five the fundamental roles that support the U.S. national security strategy as power projection, sea control, strategic deterrence, strategic sealift, and forward naval presence.[10] These roles have evolved over the course of the twentieth century. Some, such as sea control, strategic sealift, and forward naval presence, would be familiar to Alfred Thayer Mahan and Sir Julian Corbett. Others, such as strategic deterrence and power projection, are clearly the products of the twentieth century. While each of these roles has vied for ascendancy, in fact, all are integral parts of both naval and national strategy. The Department of Defense's *Joint Vision 2010* describes the challenge of providing the nation with full spectrum dominance, that is, the ability to either deter or prevail in any conflict the United States might face, while confronted with limited budgets and a diverse array of threats never before seen in the nation's history.

Forward From the Sea (1992), which was the U.S. Navy's first effort to articulate a post-Cold War strategy, built on this foundation with a shift in emphasis from sea control and strategic deterrence to the influence of events in the littoral environment that range from naval presence to full-scale combat operations.

In the absence of a peer competitor and the shrinking forces based overseas, the United States has placed a renewed emphasis on expeditionary warfare. Joint doctrine defines an expeditionary force as "an armed force organized for accomplishment of a specific objective in a foreign country."[11] In practice, the services have refined its usage to describe standing integrated forces that are capable of rapid deployment to a forward area with organic command and control. Naval expeditionary operations are presently built around the structure of a Carrier Battle Group (CVBG) and an associated Amphibious Ready Group (ARG).

The Navy Operational Concept, developed in support of *Joint Vision 2010*, envisions using this expeditionary force structure to achieve "objectives across the spectrum of the *National Military Strategy*."[12] These would include peacetime engagement, deterrence and conflict prevention, crisis response, and ultimately fighting and winning. In meeting the challenges of the next century, *Joint Vision 2010* states that "power projection, enabled by overseas presence, will likely remain the fundamental strategic concept of our future force."[13] Aside from a retaliatory nuclear strike launched from the

ballistic missile submarine force, the ultimate projection of naval power and influence is exercised with the insertion of Marine Expeditionary Forces (MEF). If a confrontation moves toward a major theater war, on-scene forces, such as a CVBG-ARG team and an Air and Space Expeditionary Task Force (ASETF), will likely play a critical role in halting or at least disrupting an aggressor's military plans. By precluding a quick victory, expeditionary forces buy the time needed to forge coalitions and assemble forces. The Navy and the Marine Corps have identified the five principal elements that are essential to the success in expeditionary warfare as maritime dominance, maneuver dominance, air dominance, firepower, and information superiority.[14]

To meet this challenge, the services envision taking a quantum step forward from the concepts of amphibious warfare employed over the last one hundred years to the new operational concept of *Operational Maneuver From The Sea (OMFTS).*[15] The Marine Corps plans to use technology to field platforms, such as the tilt-rotor MV-22 *Osprey*, to permit "ship to objective maneuver" and true "over the horizon assault." Freed from the constraints of conducting assaults over the beach, the amphibious force will operate in a battle space whose area has increased by two orders of magnitude, from 30-50 square miles to 2500-3000 square miles.[16]

Projecting combat forces ashore is one of the most challenging tasks that naval forces face. Maritime dominance is critical, in part because littoral warfare brings the naval force closer to the contested landmass. This is not a new challenge, and in fact, the most important naval battles have been fought close to shore, even though the majority of wars have been decided on land. However, as naval forces approach the adversary's coast, the defender typically gains the advantage of employing less expensive weapons systems to repel the attacker. Mines, small patrol craft, coastal submarines, land-based aviation, and shore-based missiles may all be brought to bear.

Conceptually, *Operational Maneuver From The Sea* allows the ground force commander to maximize the ability to employ maneuver warfare for striking the foe where least expected. For naval forces, the ability to remain a significant distance offshore increases the freedom of movement and complicates the enemy's calculations. However, once troops are placed ashore, the supporting naval forces become clearly tied to that operational area. While the concepts proposed in *Operational Maneuver From The Sea* increase the area of the "battlespace" by several orders of magnitude, it also has the corollary effect of requiring far greater reliance on sea-based logistics and naval fires.

The nature of the force and the capabilities of individual units define, as well as constrain, the strategy that a navy can undertake. Modernization can change a navy's ability to execute its missions in unanticipated ways, as exemplified by the challenge faced by the Royal Navy with the transition from sail to steam at the end of the nineteenth century. The United States Navy is in the throes of change today. In the case of the surface force, the development of AEGIS guided missile destroyers has produced a smaller number of vastly more capable escorts. Fully equipped to provide area air defense, these ships may ultimately be integrated into the fleet's theater missile defense architecture. However, one consequence of this mission has been to reduce the number of ships available to serve as escorts for high-value units, such as aircraft carriers, amphibious units, and merchant shipping. This trend is likely to continue as the Navy replaces 31 destroyers and 51 frigates with 32 of the new DD-21 "Land Attack" destroyers.[17]

As long as the United States remains the preeminent maritime nation, seapower will be critical to the success of its security. While the strategic emphasis may shift with the ebb and flow of competitors, the pillars of the U.S. Navy's maritime strategy will remain the forward presence, strategic sealift, and sea control that, together, remain inextricably tied to the projection of power in expeditionary warfare.

III. Evolving Maritime Threats

Maritime forces in the twenty-first century will confront a formidable array of threats. Even without the emergence of a significant competitor, the U.S. and allied navies will face unprecedented challenges from the proliferation of sophisticated missile and sensor technology. The explosion of computer technology has created a situation in which the most sophisticated weapons systems, with advanced fault-tolerant architectures, may present opportunities for less technologically advanced states. Rather than confronting the U.S. Navy directly with expensive, advanced technology ships and aircraft, a more prudent course for adversaries is to seek asymmetric advantages through the use of chemical weapons, missile technology, and other emerging technologies, all of which represent relatively inexpensive countermeasures to U.S. naval forces. The discussion in this section focuses on the threats to U.S. naval forces that technology has created.

Cruise Missiles. While mines, torpedoes, and ballistic missiles all pose significant threats to naval forces, the greatest single area of concern is probably the cruise missile.[18] It is currently estimated that roughly 70-75 countries possess cruise missiles, and of these, nineteen have produced their own missiles or have manufactured cruise missiles under license agreements.[19] The trend towards proliferation is likely to continue, as both purchasers and producers demonstrate the ability to "reverse engineer" designs from operational missiles. China has led the way with its successful production and export of the C-801 and C-802 anti-ship cruise missiles that were developed from the *Exocet* missile. The Indian *Koral* program is allegedly developing an indigenous version of the former Soviet SS-N-22 *Sunburn* supersonic anti-ship cruise missile. Given China's record of reproducing foreign designs, Russia's decision to export the SS-N-22 with the sale of *Sovremennyy* Class destroyers could lead to a new round of competition between India and China for dominance of the supersonic anti-ship cruise missile market.

The proliferation of cruise missile technology is not limited to the major powers. The Taiwanese *Hsiung Feng* II was reverse engineered from the *Harpoon*, while Iran and Iraq both developed longer range variants of the Chinese HY-2 *Silkworm* (originally developed from the Soviet SS-N-2 *Styx*). The evidence is that nations which have the capability of producing

jet aircraft generally also have the ability of producing cruise missiles, and most have demonstrated that they have an interest in doing so.[20]

The two major trends in cruise missile development have been increased speed and reduced radar signature, the latter of which is known as "stealth." Early cruise missiles, such as the *Tomahawk* and *Kingfish*, were designed with turbofan engines for long range or rocket motors for high speed, respectively. Recent advances have brought a new generation of ramjet engines, such as the French *ASMP* and *ASURA*, which are capable of speeds in excess of Mach 2. *Exocet* and other solid fueled rockets are replacing the *Styx* and other liquid fueled models. The use of solid fuel motors simplifies operations, maintenance, and logistic support, and thus makes the weapon system more attractive to the less technologically sophisticated customers. The Italian *TESEO-3* typifies advances in reducing the radar signature through shaping the missile and coating it to produce subsonic missiles that are extremely difficult to detect. As these trends continue, it is likely that technology will make increasingly sophisticated missiles available at prices that many states can afford.[21]

Remarkably flexible in application, cruise missiles have been adapted from anti-ship to land-attack missions and from ship-launched to air-launched operations with little difficulty. While only three nations (France, Russia, and the United States) are known to have developed cruise missiles that can deliver nuclear weapons, the potential exists to use cruise missiles for dispensing chemical and biological warfare agents.[22] There are public reports that China, Iran, and Syria are attempting to develop this capability.[23] Closely related to the proliferation of cruise missiles is the development of remotely piloted vehicles (RPVs). The Indian *Lakshya*, the Iranian *Baz*, and the Israeli *Delilah* all represent the class of so-called "harassment drones" that have the ability to deliver ordnance. Remotely piloted vehicles have the capability of locating and targeting naval forces operating in the littoral, and as with cruise missiles, the flight profiles of RPVs lend themselves to the dispersal of chemical or biological (CW/BW) agents.[24]

In summary, a nation that wants to challenge a major naval power for local control of the sea will probably turn to cruise missiles because these offer a relatively economical method for conducting a sophisticated attack with a reasonable probability of inflicting some damage.

Theater Ballistic Missiles. While the proliferation of theater ballistic missiles has captured considerable public attention since Iraq employed the Scud B missiles during the Gulf War, it represents a lesser threat to naval

forces than cruise missiles. There are presently about forty nations that have fielded or produced ballistic missiles, and eleven of these nations can produce nuclear, chemical or biological weapons.

However, there are technological challenges that must be addressed in order to equip a ballistic missile with a CW/BW warhead.[25] Since the most commonly deployed ballistic missiles are the Scud missiles or Scud derivatives, which are accurate within 1 kilometer, the probability of damaging a ship at sea with a conventionally equipped missile is small. Nevertheless, in certain naval operations, such as traditional amphibious landings, the resulting concentration of ships would be vulnerable to ballistic missiles that are armed with weapons of mass destruction. The trend in ballistic missile development is toward greater sophistication with improved mid-course guidance systems, such as Global Positioning System, and more accurate algorithms for calculating re-entry ballistics. The replacement of unitary warheads with sub-munitions is another low-cost option for improving lethality. In the near-term one can foresee accuracy improvements on the scale of two orders of magnitude. While their maritime role is limited, theater ballistic missile tests can be used to influence neighboring, as exemplified by the missile tests conducted by China that intimidated Taiwan in June 1996.[26]

Nuclear, Chemical and Biological Warfare. Frequently grouped under the generic heading of weapons of mass destruction, these weapons represent a significant concern for naval forces because naval warfare is a nearly ideal medium in which to employ weapons without inflicting high levels of collateral damage. Even during the Cold War, naval strategists discussed the possibility of whether nuclear torpedoes and depth bombs could be employed without necessarily escalating a crisis to a general nuclear war. While nuclear proliferation remains a serious concern in light of recent developments in India and Pakistan, the proliferation of chemical weapons is an even greater concern. If employed against naval units, chemical weapons could significantly hamper military operations even if the attack does not produce significant casualties.

The Soviet Union possessed a chemical arsenal that is estimated to have exceeded 50,000 tons of agents that ranged from phosgene, which was used during the First World War, to sophisticated nerve agents, including sarin and soman. Equally important, the vast majority of Soviet weapon systems were configured for use with either conventional or chemical warheads. The implication is that much of the military hardware in the Third World is

readily adaptable to chemical weapons. Chile, Egypt, Iran, Iraq, Israel, Libya, North Korea and Syria all reportedly have developed chemical weapons, and Pakistan is reportedly engaged in a significant chemical weapons program. For other nations or non-state actors, it is arguably possible to hire former weapons technologists or purchase the precursor chemicals on the open market.[27] Attempts to control proliferation have been seriously hampered by the fact that because many of the precursor chemicals have legitimate dual uses, a complete ban on the exportation of all possible pre-cursors is not practical. For example, when confronted with an embargo on the pre-cursor chemical needed to manufacture soman, Iraq allegedly shifted to the manufacture of sarin instead.[28]

Finally, the repeated use of CW in the Iran-Iraq War and the Soviet-Afghanistan War probably lowered the threshold for its employment in future conflicts.

Mines and Torpedoes. After cruise missiles, these weapons pose the greatest threat to naval forces conducting expeditionary warfare. The U.S. Office of Naval Intelligence estimated that there are over 150 types of naval mines in the service of at least 50 nations. These range from the simple World War I vintage contact mines that proved effective in the Arabian Gulf, to highly sophisticated propelled warhead mines, which can defend an area up to one half square mile. Even with greatly enhanced lethality, mines are expected to remain primarily a threat in shallow waters (less than 200 fathoms), and thus could pose an insurmountable obstacle to classic amphibious warfare.[29] By re-shaping the traditional doctrine of amphibious warfare, *Operational Maneuver From The Sea* seeks to reduce this vulnerability.

For an opponent seeking an asymmetric advantage, torpedoes, like mines, are relatively inexpensive weapons that can destroy high-value targets. The proliferation of sophisticated torpedoes has continued as France, Germany, Italy, and Russia are actively exporting wake-homing torpedoes. Germany has offered kits for retrofitting previous models that were sold with Type 209 diesel electric submarines, which in a littoral environment is a formidable weapon given its inherently quiet nature. However, the popularity of the submarine as the weapon of choice among Third World states may be waning, as states that purchase these weapons face the burden of maintaining complex systems. Effective submarine employment requires a cadre of skilled technicians and tacticians, all of whom need to maintain a high level of proficiency. While the threat will likely grow from those na-

tions willing to make the commitment of fiscal and personnel resources, in other cases, submarines will become expensive showpieces that have little combat capability.[30] Nevertheless, the United States is well advised to focus on the risk posed by the proliferation of torpedo technology.

Low-Observable Ships and Aircraft. The deployment of a significant number of surface combatants that employ "stealth" technology will increase in the twenty-first century. In addition to the United States, a number of states, including Sweden, Spain, Israel, Canada, Great Britain, Russia, France, and Saudi Arabia, are developing or fielding low-observable ships. Computer aided design systems have made this technology readily accessible to any ship builder, and radar absorption materials are now commercially marketed by several nations. While none of these approaches create "invisible" ships, the fact that it is much more difficult to locate and target these ships effectively enhances the effect of decoys or other countermeasures.

While true "stealth" aircraft may remain beyond the financial reach of most nations, the basic principles of radar signature management are likely to be applied in the design of future tactical aircraft. These measures will complicate the early detection and tracking of aircraft, particularly in the littoral environment. As previously discussed, the most significant advances are more likely to occur in the growing sophistication of anti-ship missiles than in the platform from which the missile is launched.[31]

Information Warfare. The information explosion has the potential to profoundly alter the conduct of war. Much has been written regarding the opportunities as well as the vulnerabilities of a globally connected information grid. Satellite imagery and communications, long the province of the major powers, are increasingly available in the world marketplace.[32] Commercial systems now routinely provide encryption and resolution capabilities that until a few years ago existed in the purely military domain. For the maritime commander, the growth of communication systems offers an unparalleled degree of connectivity and access to national resources. However, a totally new series of threats appear to be emerging, which involve weapons that are designed to destroy high-technology communication, sensor, and computer systems.

During testimony in February 1998, before the Joint Economic Committee of the U.S. Congress, an official from the U.S. Army's Space and Missile Defense Command stated that recent scientific advances in radio

frequency (RF) weapons technology by several states raise significant concerns. Broadly speaking, these weapons use high power microwave energy, in either narrow or wideband form, to disrupt or destroy the high-density metal oxide semiconductor devices that are used in modern computers and sensors. The Soviet Union long dominated the research in this field. In 1994, the Director of the Central Institute of Physics and Technology in Moscow distributed a series of papers by A. B. Prishchepenko, the inventor of compact, explosively-driven RF munitions, which described how such munitions could be employed against land mines, sea-skimming missiles, and communication systems. There is evidence that the Ukrainian, Swedish, French and Australian governments are actively investigating RF weapons technology.[33] Testimony before the same committee highlighted how simple it is to construct so-called transient electromagnetic devices. A pre-eminent example was a homemade device fabricated for under $5,000.[34] And it should be noted that the Internet has become a significant factor in the worldwide dissemination of RF weapon technology.

The development of RF weapons has profound consequences for the United States. As the most technologically sophisticated nation, the United States is vulnerable to an attack that strikes directly at the heart of its information systems. In military terms, warships bristling with communication and sensor antennae are prime targets for an attack with RF weapons. Conceptually, these weapons may offer an enemy an inexpensive and highly effective system for suppressing defenses, which would render the victim virtually defenseless against an attack with conventional guns, bombs, or missiles.[35]

The other directed energy weapon that is maturing is the laser. Since the Vietnam War, lasers have been used extensively in weapon guidance. In the late 1990s, a number of states, including France, Britain, Russia, Germany, and Israel are reportedly pursuing lasers as weapons. The Royal Navy may have fielded a shipboard system known as “Outfit DEC” as early as the Falklands War.[36] The current market leader in anti-personnel and anti-sensor laser weapons is China.[37] Over the next 15 years, the Office of Naval Intelligence predicts the development of high-energy lasers that are capable of damaging electro-optic sensors at long ranges.[38] Other sources indicate China may have already developed a limited anti-satellite laser capability.[39]

Summary. In addition to directed energy research programs, China, Russia, France, and Germany all have made significant investments in aero-

space technology. With the development and proliferation of systems that are capable of attacking a force built on information superiority, the United States must consider how twenty-first century enemies might use sophisticated, low-cost weapons to gain an asymmetric advantage in the contest for local control of the sea.[40] Such an opponent will not seek to win a battle with a major naval power, but rather to make the cost of its defeat prohibitive.

IV. Current State of Directed Energy Technology

Fascination with directed energy weapons has pre-saged the development of that technology by several generations. Indeed, some have drawn the line back to the legend that Hippocrates' defended Syracuse by using Archimedes' idea of reflecting sunlight to destroy the Roman fleet. Others have traced its roots to science fiction writers, such as Jules Verne and H.G. Wells. In 1938, Generals "Hap" Arnold and Ira Eaker wrote that defense against aerial attack was practically impossible until science developed new inventions such as "an electric ray which has been given credit for being able to stop gasoline engines by putting out of commission their electrical system."[41] Less than ten years later, U.S. Navy scientists proposed using directed energy in the form of radio waves to defeat atomic weapons before they could reach their targets.[42]

While the theoretical birth of the laser is ascribed to Albert Einstein's prediction of "stimulated emission," in practical terms the laser was the outgrowth of the work of Arthur L. Schawlow and Charles H. Townes on an optical Microwave Amplification by Stimulated Emission of Radiation (MASER). Others pioneering in the field included the Soviet scientists, Aleksander M. Prokhorov and Nikolai Basov, as well as a Columbia University graduate student, Gordon Gould, who independently reached the same conclusions and, in fact, coined the term laser. The Hughes Corporation physicist Theodore H. Maiman in May 1960 demonstrated the first ruby laser. Replacing the term optical MASER, lasers entered the vernacular as an acronym for Light Amplification by Stimulated Emission of Radiation. While sharing common roots in the MASER, laser and high power microwave research diverged rapidly over the succeeding decades.

Confronted with the nuclear arms race, the Department of Defense looked eagerly at laser technology as a means to counter the seemingly unstoppable threat posed by inter-continental ballistic missiles. The Advanced Research Projects Agency became an early sponsor of Gould's proposal to build a laser.[43] In 1958, the DOD inaugurated a research and development program, known as Project Defender, to search for viable anti-ballistic missile technologies. Under the charter of Project Defender, the Office of Naval Research managed Project Seaside, which sought to determine whether a ruby laser could be used as an anti-ballistic missile system. Given its expertise in nuclear warheads, the Air Force was commissioned to study the energy necessary for a laser to destroy an ICBM.

This 1962 study marked the genesis of the team that was to develop the Airborne Laser Laboratory and, ultimately, the Airborne Laser.[44]

Laser Technologies

Of all the approaches to using directed energy, lasers are probably the most familiar. Broadly speaking, laser technology has matured rapidly over the last thirty-five years. From the beginning, commercial research has been as important as that sponsored by the military. The widespread use of compact, inexpensive, low-power lasers attests to the growth of the technology. The commercial and military applications of so-called low energy lasers, which range from CD players to laser guided bombs, are well known. While not as rapid as some proponents had hoped, there has been significant progress in military applications.

Regardless of application, lasers are generally categorized by the substance being lazed (gas, liquid, or solid) and the method of stimulation or "pumping" (pulse discharge, electricity, or chemical reaction) used. The product is a beam of coherent light at a given wavelength.[45] The third component of most laser systems is a resonant optical cavity, which provides the means for increasing the energy in the beam and extracting that energy. In its simplest form, a resonator can be a pair of optical mirrors, one of which is only partially reflective. As the beam traverses back and forth through the lazed media, the photons in the beam stimulate further emissions. In actual practice, there are a variety of resonator designs as well as systems that employ other methods of amplification.[46]

The reason that lasers have important military applications is related to the unique characteristics of the beam. Unlike ordinary incandescent lights that scatter energy in a random fashion, the beam produced by a laser can be highly collimated. Consequently, the energy deposited on an area of one square centimeter by a 100 watt laser may be as much as nine orders of magnitude, that is, one billion times greater than the energy deposited by a 100 watt incandescent lamp.[47]

While it is common to describe lasers as monochromatic, i.e., consisting of a single color or wavelength, this is somewhat inaccurate. For a wide variety of reasons, lasers normally operate across a relatively narrow band of wavelengths at which significant amounts of energy are radiated.[48] However, the outputs of certain types of lasers can be adjusted. For example, the output of typical chemical dye lasers may be tuned from the near-ultraviolet

to the near infrared. Free electron lasers are also theoretically capable of tuning across wide bands. Other methods of adjusting wavelengths include optical techniques and Raman shifting. As one might expect, all of these approaches involve significant penalties in complexity, which translate directly into increased cost and decreased reliability.[49]

The type of material employed in the optical cavity may categorize a laser. There are four major types that appear to have applications for directed energy weapons. Solid state lasers use a non-conductive glass or crystalline material that is doped with a species, such as, neodymium or erbium, as the active medium. The prime example would be the original ruby laser. Chemical lasers use the reactions of gases or liquids to create the excited energy states necessary for laser emission. Semi-conductor (or diode) lasers use the current flow through an electrical junction to excite the electrons. At low current densities, the device functions as a light emitting diode. However, if the system is designed with optical feedback, the current density can be increased to a sufficient level that the diode will operate as a laser.[50] The most common application of this type of laser is found in compact disc players. The fourth category is the ubitron or free electron laser. This device, which more closely resembles a high voltage linear accelerator, is capable of producing high power radiation across a broad band of frequencies.

Diode Pumped Solid State Lasers. During the 1960's and seventies, solid state lasers enjoyed considerable popularity in military applications, such as range-finders. There has been a renewed interest in the possible weapons applications of solid state lasers following significant technical advances that have occurred during the last five to seven years. In 1995, a DARPA-Army sponsored, diode pumped laser, developed by TRW, demonstrated a power output of 250 watts with a 100 Hz repetition rate. In spite of this progress, advances in three major areas will be necessary for solid state lasers to become viable candidates for high power military applications. The first is the diode cost, typically $10-$20 per watt peak power, which makes them impractical for applications requiring 10 kW or higher. The second is the relatively low net efficiency, on the order of 9-15 percent. And the third is the intolerance of high temperatures, which complicates the transfer of waste heat. The need to dissipate large amounts of heat imposes mass flow requirements that are analogous to those encountered with gas combustion lasers. Thus, for military high power applications, the inherent size advantage of the solid state laser is offset by the need for a system that can handle large volumes of cooling medium.[51]

Recent advances with indium gallium arsenide diode arrays and ytterbium doped laser crystals offer significant improvements in waste heat reduction and increased pumping efficiency. Another concept is to treat the thermal capacity of the laser as a "magazine" that defines the total energy output of the weapon over the firing cycle. The weapon is reloaded by cooling the laser. Assuming a yield of 500-1000 joules per cm^3 of host material, approximately 10-15 kg would be required for each megajoule of magazine capacity. The Air Force estimates that the minimum energy needed to destroy small tactical missiles will be less than 100 kilojoules.[52] This approach has the advantage of a "magazine" that only requires cooling to "reload." This frees the firing platform from the need to return to a fuel or ordnance depot to re-arm.

The potential for a compact system that uses environmental cooling makes the diode pumped solid state laser an attractive candidate for use on tactical aircraft. While the path to the development of such weapons appears straightforward, there are still significant challenges to be overcome. Reasonable estimates put the availability of this technology between 2015 and 2020.[53]

High Power Semi-conductor Lasers. Building on the commercial success of the early 1980's, the high power semiconductor laser technology (HPSLT) program at Phillips Laboratory has achieved an increase in output power of two orders of magnitude since 1984. Semiconductor lasers offer the greatest efficiency (by a factor of at least four) when compared with other laser designs. Compact, solid state, and based on microelectronics, they offer superior reliability at minimum cost. Initial demonstrations indicate that semiconductor lasers can be employed in phased arrays that will be scalable to high power applications.

The Air Force's "Foto-Fighter" concept relies heavily on the use of embedded arrays of semi-conductor lasers as sensors and weapons. The emphasis in the high-power semiconductor laser technology program has been to improve the power output of each element, to develop alternate frequencies, and to design coherent arrays. While most of the research to date has been done with aluminum gallium arsenide and indium gallium arsenide, other materials, such as antimony, offer the promise of broader bandwidths. The stated goal is to incorporate devices that produce good beam qualities for both offensive and defensive applications.

A related development is the use of a semiconductor laser to pump a single fiber laser that uses a rare earth dopant as its fiber core. By expanding

upon the work done to produce a 1000 element linear semiconductor array, a 10,000-beam fiber optic laser weapon may be feasible. For aircraft applications, the improvements in aircraft performance and reliability gained by eliminating high-drag turrets and mechanically complex tracking systems are obvious. Equally appealing is the possibility of fielding a more robust and responsive weapon that is scanned electronically.

Chemical Lasers. The greatest successes in high power lasers attained to date have been in the field of chemical lasers. The three that appear to offer the greatest potential are the hydrogen fluoride laser, the deuterium fluoride laser, and the carbon dioxide iodine laser. The hydrogen fluoride and deuterium fluoride lasers, which were initially developed by the United Technologies Research Center in the late 1960's, operate on the same basic principles.[54] The hydrogen fluoride laser produces wavelengths between 2.7 and 3.3 microns, in the infrared region where atmospheric absorption is strong. Because of its heavier atomic mass, the hydrogen isotope deuterium produces a longer wavelength emission. Deuterium fluoride lasers emit in the 3.5-4.2 micron region where the atmosphere is more transparent.

The differences in absorption characteristics led initially to two different sponsors. With its shorter wavelength and therefore smaller optics, the hydrogen fluoride laser is considered a leading contender for the Ballistic Missile Defense Organization's Space-Based Laser program. On the other hand, the deuterium fluoride laser is the basis for TRW's Mid-Infrared Advanced Chemical Laser (MIRACL). While originally developed in the 1970's for the U.S. Navy, the latter is now serving as the basis for the Nautilus Tactical High-Energy Laser (THEL) demonstrator that is being co-developed with the Israeli Ministry of Defense.[55]

The MIRACL is the only operational megawatt class laser in the United States. Employed with the Sea-Lite Beam Director system, it has completed a number of successful demonstrations, including the shootdown of five sub-sonic BQM-34 drones in 1987 and the successful engagement of a supersonic *Vandal* missile target in 1989.[56] In February 1996, the U.S. Army used the MIRACL/Sea-Lite Beam Director to successfully destroy a short-range *Brant* rocket in flight. In 1997, the MIRACL/Sea-Lite combination demonstrated the ability to illuminate satellites on orbit.[57] In spite of these successes and the contractor's proposal for an engineering model demonstration at-sea, the Navy determined that the deuterium fluoride wavelength was unsuitable. It subsequently loaned the equipment to the U.S. Army for the latter's THEL program.[58]

The U.S. Air Force pursued the alternative approach of developing the Chemical Oxygen Iodine Laser (COIL) from its Ground Based Laser Technology program.[59] Because of its shorter wavelength, the optical systems associated with the COIL are substantially smaller than those in either the hydrogen fluoride or deuterium fluoride lasers. As with the deuterium fluoride laser, the COIL is subject to significantly less water vapor absorption than the hydrogen fluoride laser. Given these characteristics, the decision was made to develop a multi-module megawatt class COIL for the Airborne Laser (ABL).[60] The ABL builds on the success of the Air Force's Airborne Laser Laboratory, which demonstrated that missiles could be successfully engaged and destroyed by a laser mounted in a NKC-135 aircraft.[61]

Free Electron Laser The ubitron, also known as the free electron laser, is the product of extensive work by the Strategic Defense Initiative Organization.[62] While the initial intent was to develop a free electron laser as a weapon, current research suggests that it may be most useful as a device to produce high-power microwaves.[63] The Navy is continuing to support modest research in FEL technology for the possible development of a short-range anti-ship missile defense system.[64]

Laser Optics. Optical systems provide the path needed to focus and direct a laser beam so that the energy can be usefully employed. High-energy lasers pose particular challenges for optical designers because the devices must be able to withstand the deposition of substantial amounts of energy. As the Airborne Laser Laboratory demonstrated, the optical path from the laser to the aperture is critical. Aberrations in the HEL's gain medium, imperfections in laser optical surfaces, atmospheric and vehicle turbulence, and imperfections in the beam director all require compensation if sufficient energy is to be deposited on the surface of the target.

In view of the tremendous ranges involved in ballistic missile defense, the Air Force has focused considerable research on atmospheric turbulence and methods of compensation. The result has been a series of breakthroughs that demonstrated the feasibility of using adaptive optics to compensate for atmospheric turbulence as well as distortions induced within the device's internal optical path. The Air Force Research Laboratory's Phillips Research Site has successfully demonstrated the use of a deformable mirror system to effectively pre-distort laser beams. The adaptive optical system employs hundreds of small actuators that deform the surface of the mirror in response to atmospheric scatter sampling data to eliminate, or "null out,"

atmospheric distortion. The Air Force is continuing to examine potentially less complex alternatives.[65] While critical to the success of certain high-energy laser applications, earlier experiments demonstrated that these technologies are not essential for lasers employed at tactical ranges of less than 20 kilometers.[66]

Tracking and Fire Control Systems. To achieve the most rapid destruction of the target, a laser weapon must deposit the maximum amount of energy on the smallest possible area of the surface of the target. This constraint puts high demands on the tracking and fire control systems associated with a laser weapon.[67] One advantage of laser weapons is the incredible speed differential between lasers that operate at the equivalent of Mach 1,000,000 and missiles at speeds of Mach 2-3. Even a hypersonic missile will move only a comparatively short distance during the time it takes for a laser to engage it. The ultimate successes of the Airborne Laser Laboratory, the Sea Lite Beam Director, and the Nautilus program all demonstrate that the basic technology for laser tracking and fire control systems is available. While the Sea Lite Beam Director was deemed to be too large for shipboard installation, its developer was confident ten years ago that a downscaled engineering development model was feasible.[68]

Laser Limitations

While size, weight, volume, power, and cooling requirements dominate discussions of airborne and space-based laser applications, the greatest challenges for terrestrial or sea-based system originate from atmospheric effects. The effects of turbulence have been discussed and, as noted, atmospheric turbulence is a limiting factor for strategic applications, such as the using the Space-Based Laser or the Airborne Laser for missile defense. For tactical applications, atmospheric turbulence is just one environmental factor to be considered along with absorption, scatter, and thermal blooming.

Absorption. In simplest terms, only photons at specific wavelengths are absorbed because the energy levels that exist in a given molecule are present in discrete states. Therefore, only a single spectral line is absorbed for each excited state. In practice, a broadening of spectral lines results in a series of so-called “window regions” or ranges of wavelengths in which absorption is relatively weak.[69] In the infrared region, water and carbon dioxide molecular absorption defines the window regions. At millimeter and microwave

wavelengths, absorption by diatomic oxygen and water molecules is the predominant factor. The characteristic windows used for military applications have traditionally been the 8-12 micron and 3-5 micron windows. The COIL exploits the window at 1.3 microns.[70]

Absorption and refraction significantly influence the use of lasers for terrestrial and maritime applications. The lower portion of the atmosphere, the troposphere, extends to a nominal altitude of 11 kilometers, or approximately 36,000 feet. Most of the principal atmospheric attenuators, including water and carbon dioxide molecules, clouds, fog and other aerosols, are found in this region. While the amount of water vapor present is highly dependent upon seasonal and weather variations, it is the predominant factor in the maritime environment. In addition to absorption by individual water molecules, water vapor also influences particle scattering.[71] The effect of these variations is to make atmospheric predictions difficult.

Scattering. For the purpose of this discussion, atmospheric particles can be divided into two groups, aerosols and hydrometers. The first group has an average radius of less than one micron. Scattering by aerosols is significantly greater than the molecular scattering described above.[72] On the other hand, hydrometers or water bearing particles tend to be substantially larger than one micron. Given their larger size, they do not remain suspended, but instead are removed by coagulation, fallout, or washout. Again, the widely varying sources and methods of distribution make it difficult to predict how the propagation device for a laser will perform on any given day. In addition to these natural challenges, there are also military obscurants that have median particle diameters ranging from 0.6 to 3.4 microns.[73]

Thermal Blooming. As a high-energy laser beam propagates through the air, small amounts of energy are transferred to the molecules along its path. The heated air expands and effectively creates a lens, which distorts the laser beam. This spreading effect is generally referred to as thermal blooming. While an annoyance for low power laser applications, such as illuminating a target for destruction with a conventional weapon, blooming can become a limiting factor in the efficiency of high-power lasers. While wind and beam motion are significant factors in determining the magnitude of the effect, thermal blooming poses the greatest single challenge for laser applications in the troposphere.[74]

Summary. Laser technology has matured greatly over the last forty years. While the development of higher power and more efficient devices continue

to progress, the significant fact is that lasers have the demonstrated ability to destroy missiles. Terrestrial and maritime lasers capable of delivering sufficient power for weapons applications appear to be feasible without major technological innovations. The limitations imposed by tropospheric propagation phenomena are still undetermined, but it must be understood that this could ultimately compromise the effectiveness of laser-based systems for air defense.

Radio Frequency Weapons Technologies

The second major category of directed energy weapons are the Radio Frequency (RF) devices. Rather than operating in the infrared, visual, or ultra-violet spectra, these devices operate in the communications, navigation, and radar frequency bands from approximately 100 MHz to 10 GHz. Radio frequency devices are typically sub-categorized as either High Power Microwave (HPM) or Ultra-Wideband (UWB) systems.*

Origins. With their origin in the radio and radar devices developed in the first half of the twentieth century, microwave devices pre-dated the development of lasers. Indeed, World War II had proven the value of microwave technology for communications and sensors. The 1970's saw the commercialization of microwave technology as the microwave oven became a household fixture. While much of the radar and communications research in the military focused on signal processing in a never ending drive to extract ever smaller signals from an increasingly noisy environment, significant progress was made in the development of new transmission systems. New solid state transmitters were developed and electronically scanned phased arrays began to replace simple mechanically scanned antennas in many applications.

There were separate efforts to examine the effects of the electromagnetic pulse associated with the detonation of nuclear weapons. While the 1957 edition of *The Effects of Nuclear Weapons* did not directly address electromagnetic pulse phenomena, the latter were included in the 1964 revision

* High-power microwave devices typically operate at frequencies between 1-20 GHz with large pulse widths (on the order of one microsecond) and relatively narrow bandwidths (nominally one percent of the frequency, which equates to approximately 10 MHz at the lower end and as much as 100 MHz at the upper end). Ultra-wideband systems are characterized by narrow pulse widths of less than 100 nanoseconds and bandwidths that may exceed 50 percent of the center frequency. Typical wideband devices have bandwidths that range from 200 MHz to 3 GHz.

and filled an entire chapter in the 1977 edition.[75] Scientists learned that EMP was a likely cause of the electronic equipment malfunctions that were encountered during atmospheric testing. One publicized example was the large-scale failure of streetlights on the island of Oahu, which was caused by a high-altitude detonation 500 miles away at Johnston Island. The failure was traced to "over-current protection" devices that were installed in the system's transformers. There were anecdotal reports that "hundreds" of burglar alarms in Honolulu began sounding at the same time.[76]

The cessation of atmospheric testing in 1962 forced scientists to seek other means to examine the EMP phenomena. Both transmission line and radiating simulators were developed to produce representative fields. While not exact replications of the post-detonation environment, they provided a great deal of data on coupling mechanisms, circuit vulnerabilities, and weaknesses in system design. They also provided the impetus for the exploration of EMP as a weapon.[77]

During the Cold War, the Soviet Union developed an extensive research program in high-power RF technologies. Soviet work included the successful development of the Magnetically Insulated Linear Oscillator (MILO), a device which was invented in the United States, but later abandoned in the 1980's. The Soviets also exploited the work of Andrei Sakharov on the Magneto-cumulative Generator (MCG) for the development of explosively-driven power supplies. Since the 1991, Russia and other newly independent states are reported to have used MCGs to drive ultra-wideband and high power microwave sources, lasers, and rail-guns.[78] Concern in the West solidified in 1994 when General Loborev, Director of Moscow's Central Institute of Physics and Technology, distributed a paper by A. B. Prishchepenko that described how to employ an explosively-driven RF weapon.

Characteristics. High power RF systems are distinct from traditional electronic warfare systems. Rather than simply deceiving the victim with random noise or false targets, the goal of both HPM and UWB devices is to overwhelm the ability of a target to reject or disperse RF energy, which then leaves the victim system susceptible to disruption or destruction.[79] Rather than relying on the target system's signal path as electronic warfare systems do, high power RF techniques exploit electrical pathways to vital subsystems.

In general terms, there are two pathways that may be employed to reach a susceptible subsystem. The first path is the so-called "front-door" that di-

rects energy at the antenna. If the microwave energy is directed at a frequency that falls within the design bandwidth of the system, the target may be particularly vulnerable since its receiver is designed to detect and process the relatively weak returning signals. Out-of-band signals may also couple with the antenna system and overwhelm the signal processor. While narrow band HPM systems can be particularly effective using front door techniques, their success relies upon an understanding of the target's design characteristics.

The second path of susceptibility is so-called "back-door" coupling. This refers to any radiation coupling that follows a path other than that which exists through the antenna. Cracks or gaps in an airframe, exposed wires, or any other conductive material can provide a path for energy to reach key electronic components. While back-door paths require higher energy levels before damage is likely to occur, they are typically much more difficult to eliminate.

The increasing reliance on metal oxide semiconductor devices increases the vulnerability of electronic components to EMP effects.[80] While there has been extensive work on the effects of a nuclear generated EMP, those data reflect the lower characteristic frequency band and longer pulses seen in nuclear detonations and may not be applicable to the disruption and damage caused by high-power microwave devices. For example, the shorter pulsewidths of HPM and UWB obviate the current protection methods used against nuclear EMP. While the strength of nuclear electromagnetic pulses decreases rapidly above the Very High Frequency (VHF) band (30-300 MHz), UWB devices cover the spectrum from hundreds of megahertz into the gigahertz range. Moreover, HPM devices routinely operate at frequencies up to tens of gigahertz. The fact that the shorter HPM and UWB pulses are faster than the response time of typical limiters means that the targeted system can be damaged or destroyed before the protection circuit reacts. At the other extreme, there are devices with long duration (millisecond) pulses that can cause significant damage.

Potential RF weapon sources may be categorized by their bandwidth, pulse duration, and the energy source used to drive the device. There are three types of pulsed power systems generally under study: capacitive, inductive, and explosive. As previously discussed, recent attention has been devoted to the possibility of developing explosively driven RF munitions.

Power Systems. There have been proposals for RF devices that would convert the chemical energy of an explosive reaction into magnetic energy,

which would then be converted into electrical energy, and finally into microwave energy. While this is an inherently inefficient process, chemical explosives are a readily available energy source. The projected yields of the proposed devices are relatively small.[82] To be effective, the weapon would have to detonate relatively close to the target (within a kilometer or less) in order to exploit the inherent lack of shielding in most sensor and weapon systems today.

An alternative approach is to develop electrically driven devices that can eliminate two of the energy conversion steps and can provide a multi-shot capability.[83] Early attempts were hindered by the need for a large external power supply and energy storage system, such as a massive bank of capacitors. These limitations may be overcome by emerging technologies. The first technology entails a set of solid state pursers developed at the Ioffe Physico-Technical Institute in St. Petersburg, Russia. The system uses nanosecond and picosecond switches to develop 10 nanosecond, 10 kHz pulses for a ground penetrating geological sensor. One observer has reported that such devices could be used to construct a briefcase sized, adjustable jammer that is capable of delivering 100 kilovolts per meter at 5 meters. Related technologies include a high-current electron accelerator known a RADAN that has claimed an output power in excess of 5 MW, using a 12 volt battery power supply, as well as the Russian built NAGIRA radar that demonstrated a 300 MW peak power.[84]

Alternatively, pulsed power systems that use inductive storage devices are appealing because they can store more energy per unit volume with a magnetic field than an electric field. To date, limitations in switching technology have precluded their widespread use. Both inductive and capacitive pulsed power systems will require further development if they are to provide weapons with a multi-shot capability.[85]

Microwave Sources. A wide variety of HPM narrowband sources have been developed over the years. In addition to the magnetically insulated linear oscillator previously mentioned, a number of other technologies are possible.[86] Current technology has produced a 25-gigawatt ultra-wideband source, a 100-gigawatt UWB device is anticipated within a year, and finally, travelling wave devices are also being explored for UWB applications.

Ultra-wideband Devices. Freed from the need to be precisely tuned at a particular frequency, ultra-wideband devices are generally limited by switching technology and antenna design. There are two common ap-

proaches to switching devices. The first, spark gap switching, was described in congressional testimony as a candidate for use in a "homemade" Transient Electro-magnetic Device.[87] While it offers a simple and inexpensive solution, the device's lengthy recovery time between firings makes it better suited for single shot applications.[88] While the development of suitable solid state switches has been more difficult, there has been progress with the use of photoconductive semiconductor switches that are triggered by a laser. A number of other approaches are also under investigation.

Antenna design for ultra-wideband systems poses unique challenges. The very nature of a wideband system makes interference with a number of friendly surveillance and communications systems possible. To avoid such problems the directionality (pointing) of the transmitting antenna is critical. Most current UWB systems use Transverse Electro-Magnetic (TEM) horns.[89] A variation of the TEM horn, known as the Impulse Radiating Antenna (IRA), adds a parabolic reflector. The Phillips Research Site has succeeded in demonstrating an IRA that provides a conical beam whose width is approximately one-degree. By focusing the energy in such a narrow beam, the impulse radiating antenna makes it possible to dramatically reduce the potential for fratricide, thereby making the employment of an ultra-wideband device feasible in an operational environment. Research continues into alternatives that would permit the use of conventional dispersive antennas by pre-distorting the signal so that the desired output is obtained. Additional theoretical work is attempting to develop an antenna with broadband characteristics that range from the low megahertz range to multi-gigahertz frequencies.

Summary. While each of these devices has advantages and limitations, the significant progress made in the last ten years strongly suggests that high power RF weapons can be produced within the next two decades. A key factor will be the development of devices whose waveforms minimize atmospheric breakdown. Other critical technologies that require further development are reliable, compact, pulsed power systems, higher power microwave sources, solid state switching devices, and impulse radiating antennas. The development of planar arrays with electronic steering to support both HPM and UWB systems is highly desirable from an operational perspective.[90]

Comparison of RF Weapon and High-Energy Laser Technologies

Many researchers have recognized that these two forms of directed energy provide complimentary capabilities in the development of weapon systems. Lasers are precise; however, their precision requires complex pointing and tracking systems. By contrast, RF systems offer area coverage with less stringent demands for target tracking; however, the penalty is to reduce the ability to discriminate between friend and foe. While a narrow laser beam has the potential to deliver greater energy at point targets over long distances, such systems can be severely degraded by weather and atmospheric conditions. On the other hand, while RF systems are limited to substantially shorter ranges even under the best conditions, they have the distinct advantage of suffering only modest attenuation due to weather and atmospherics.

The research community has made tremendous strides over the last decade. A reasonable estimate is that both technologies are on the verge of further advancements that will enhance their value as weapons. Nonetheless, the fundamental physical differences between lasers and RF systems leave the operational advantages of each relatively unchanged (See Table 1).

While neither of these technologies is fully mature, nothing in principle precludes their successful development as "speed of light" weapons. Recent analyses have indicated that the volume, weight, power, and cooling requirements of these technologies may limit airborne and space-based applications for the foreseeable future.[91] Nevertheless, the US Air Force Scientific Advisory Board is guardedly optimistic about the feasibility of developing laser and RF weapons for fighter aircraft over the next thirty years.[92]

Cost is a constraint with the present state of the art, particularly for any application that involves a significant number of platforms. In the long term, however, cost does not appear to be an insurmountable obstacle. The continuing commercial demand for improvements in the manufacturing of electronic components is likely to reduce the cost of components. While it is unrealistic to expect that the trend toward lower unit costs over the last decade will continue unabated, the demands placed upon the commercial electronics market should further reduce costs.[93]

Table 1. Comparison of RF Weapon and High-energy Laser Technologies[94]

RF Weapons	High-energy Lasers
Generally affects targets from the inside out. Mechanism is electronic destruction or disruption.	Generally affects targets from the outside in. Mechanism is typically structural destruction.
Wavelengths from 0.1 cm to 3.0 m. Invisible.	Wavelengths from 0.27 microns to 5 microns. Visible to infrared (invisible).
Relatively weather insensitive. Clouds and dust are not major factors.	Environmentally sensitive to clouds, dust, and molecular absorption.
Monolith and/or phased emitters.	Generally monolith. Phased arrays under development.
Generally large apertures, metal antennas, ground planes. Relatively durable.	Modest apertures, glass mirrors, coatings and cleaner transmitters needed. Optical surfaces more susceptible to damage.
Relatively large beamwidths. (Minimum on the order of 1 degree.) Typically flood the target with radiation. Possibility for illumination of multiple targets simultaneously.	Extremely narrow beams. Uses small laser spot to surgically attack individual target. Requires precise target tracking. Limited to engaging one target at a time.
Both approaches share the following characteristics: Destructive power travels at the speed of light. Capable of graduated effects from degrade, disrupt, damage and destroy.	

Source: Adapted from Barry Hogge, Chief Scientist, Directed Energy Directorate, Phillips Research Site, "Assessment of the SAB Aerospace Expeditionary Force Studies Recommendations," May 1, 1998.

As previously discussed, there are certain physical limitations with both of these directed energy technologies that significantly limit their military utility. For lasers, the principal limitations are atmospheric effects, mechanical scanning, and the maximum power that can be delivered. The absorption and scattering effects will preclude lasers from becoming true all-weather weapons in the near term, even if the transmissivity window in the one-micron region could be exploited. Moreover, any sensor limited to a single relatively narrow band is vulnerable to counter-measures.[95]

Thermal blooming is the most significant long-term challenge because it offsets many of the advances in power generation. Beyond a certain point, simply adding more power is not the answer. Further research in pulse shaping and dwell times will be necessary to overcome these limitations. As the National Research Council suggested, it is unlikely that the ability to

deliver laser power will keep pace with the efforts to harden the nose cones of missiles. Before deciding whether the challenge can be solved, one must understand that historically missiles have been successfully engaged when lasers are directed at control surfaces and fuselages from oblique aspects.[96] It is likely that a missile, which maneuvers to avoid other defensive systems, could be engaged by a laser.

Current laser systems generally employ mechanically scanned apertures, but these have two disadvantages. The first is to increase the response time required for mechanically slewing, or pointing, the laser. The second, seemingly mundane issue, is the increased complexity of providing a protective cover for the aperture that protects it from environmental damage while not interfering with the transmission of high-power laser energy. The development of large planar laser arrays, as proposed in the *New World Vistas* study, provides a long-term solution to both of these problems.[97]

The evidence from the first phase of the USAF study "Directed Energy—Applications in Tactical Airborne Combat" (DE-ATAC) is that microwave devices have the greatest potential in the near term. This includes applications in enhanced munitions, large and small aircraft self-defense, and integrating directed energy into unmanned combat air vehicles (UCAV) for suppressing enemy air defenses (SEAD).[98]

Nevertheless, RF directed energy weapons still face a number of physical limitations. As transmitted power is increased, high-power microwave weapons confront the problem of air breakdown. Current research efforts are devoted to identifying waveforms that permit the maximum transfer of energy without reaching the breakdown threshold. Propagation losses can limit the effective range of RF systems, since even a focused beam spreads dramatically as the range to the target increases.[99]

Narrow band HPM systems typically have better transmission characteristics and fewer problems with fratricide than wide band systems, but narrow band systems require some prior knowledge of the threat and can be defeated by hardening. However, ultra-wideband microwave systems offer broad coverage of the threat even when one has little or no knowledge of the enemy's system. With less energy being transmitted at a given frequency (fewer watts per megahertz), current UWB systems have significantly shorter effective ranges than narrow band systems. Research continues in efforts to build a true "dispersion-less" antenna that would increase the tactical ranges of UWB systems without further complicating the fratricide/suicide problems.[100]

Any conclusions about the viability of directed energy weapons must be understood in the context of the potential applications. The United States has focused on the use of directed energy weapons for anti-missile defense (both cruise and ballistic). As the DE-ATAC study addressed, there are several other applications that could be adopted by potentially hostile nations. It is not prudent to forego the development of directed energy weapons because they do not provide a complete solution to the anti-missile defense problem. Finally, it is evident that directed energy devices offer a new form of weapons that can deliver lethal power at an unprecedented speed. The likelihood that some nation will choose to build such weapons means that U.S. forces will be placed in jeopardy if they are not able to respond to this threat. For now, RF weapons and high-energy lasers appear to offer the best methods for countering the threat of attack at the speed of light.

V. Directed Energy and Fleet Defense

This section focuses on a framework for understanding how directed energy systems may contribute to fleet defense, and in particular with developing a more robust capability against new generations of anti-ship cruise missiles. The broader argument is that the inherent flexibility of directed energy systems makes them attractive candidates for other missions, including the neutralization of small fast patrol boats, sensor blinding, and other anti-surveillance measures.

Anti-ship Missile Defense

As previously discussed, advanced anti-ship cruise missiles pose the greatest threat to major naval powers in the foreseeable future. Directed energy systems provide two primary mechanisms and one secondary mechanism for cruise missile engagement and destruction. The primary methods are to disrupt or disable the missile using electromagnetic effects produced by an ultra-wideband microwave system, or to destroy a non-maneuvering missile with a surface-to-air missile. Because of its susceptibility to environmental limitations, a laser system may be unavailable when needed. Therefore, direct destruction with a high-energy laser is defined as a secondary mechanism, even though it will be the first system to engage threats in tactical situations.

An ultra-wideband microwave system can be used to induce the transient effects of disturbance and upset, as well as the more lasting effects of latch-up or burnout.[101] The specific effect is less important than the fact that some disturbance is introduced. The greater the missile's speed and the lower its altitude, the more susceptible it will be to minor perturbations in its guidance and control system. Sea-skimming missile systems require extremely fast control systems to avoid flying into the water even in relatively benign weather. A Mach 3.0 missile (3000 feet per second) flying 30 feet above the sea travels approximately 150 feet during a 50 millisecond disruption. Thus, even a minor disturbance of the missile's radar altimeter or guidance software could be sufficient to create a "hard kill" if the missile hits the surface of the sea. If sufficient energy can be deposited to induce latch-up or burnout, the probability of kill increases. An ultra-wideband source eliminates the need for specific knowledge about the enemy missile because it is not necessary to target specific mechanisms in the missile. The wider the fre-

quency coverage of the UWB device means that it is more likely to disrupt or damage the missile.

An alternative mechanism employs a high-energy laser system to detect, track, and engage the sensor that guides the incoming missile. For missiles coming in head-on, it may be difficult or impossible to obtain a structural or payload kill. While the radome itself may be susceptible to damage, the physical placement of the guidance and control systems within the missile body may preclude a direct kill.[102] However, once the missile's sensor system has been damaged or destroyed, it is more vulnerable to both microwave disruption and direct attack. Typically, cruise missiles are programmed to fly to the last known target location if sensor data are lost. When the ability of the missile to maneuver is eliminated, it dramatically increases the probability that a conventional surface-to-air missile, such as the RIM-116A, can destroy the missile. Alternatively, if an incoming missile is deprived of sensor updates, it will be unable to reacquire the target and adjust its track when its guidance system is momentarily disrupted by microwave illumination.

Crossing targets, which are targets that approach a unit's defensive perimeter tangentially, generally pose the greatest difficulties for conventional air defense missile systems, but these are also the most vulnerable to destruction with lasers. A variety of test programs have demonstrated that terrestrial and airborne laser systems can successfully engage missile targets in crossing scenarios.[103] While such targets traditionally were engaged by area defense systems, the trend towards increasingly sophisticated anti-ship missiles means that point-defense systems must now confront maneuvering missiles. In collaborative defense, the attacker is faced with the dilemma of maneuvering to defeat point-defense missile systems and risking destruction by a high-energy laser. The alternative is to proceed directly at the target to minimize the ability of the laser to engage it, while maximizing the probability of successful engagement by a surface-to-air missile. Table 2 compares the performance of high-energy lasers against head-on and crossing missile targets.

Table 2. High-energy Laser Lethality against Missile Threats[104]

Kill Assurance	Effective Range	Type Kill	Aim Point	Engagement	
				Head-on	Crossing
High	Short	Structural	Propulsion System	No	Yes
			Structural Member	No	Yes
		Payload	Warhead	No	Yes
			Propellant	No	Yes
		Aerodynamic	Radome	Yes	No
			Control Surfaces	No	Yes
		Control System	Autopilot	No	Yes
			Other electronic control systems	Yes	No
		Sensor Destruction	RF & EO Seekers	Yes	No
			Imaging Sensor	Yes	No
		Sensor Dazzle	E/O Seeker	Yes	No
Low	Long		Imaging Seeker	Yes	No

Source: Adapted from briefing materials provided by Mr. Young Cook, NRL, Washington, DC, from a presentation to the 1st Directed Energy Symposium, Kirtland AFB, New Mexico, November 6, 1998.

The tendency to increase the speed and reduce the signature of anti-ship missiles makes it increasingly problematic to defend against these missiles. A Mach 4.0 missile skimming the waves at 3 meters could be engaged for approximately 20 seconds from the time that it became detectable. This leaves very little time for track detection, acquisition, identification, and hand-off to a weapon system, and in that case the time of flight of the intercepting missile significantly affects the success or failure of engagement. The defender has an inherent disadvantage because the intercepting missile must accelerate from zero to Mach 3.0+ in a matter of seconds. Even if the defending missile is fired at the moment the attacker crosses the radar horizon, the maximum intercept point will be approximately 7 nautical miles from the defended point. There is a finite amount of time to train and elevate the launcher for each engagement, as well as to initiate the ignition sequence for each missile fired. With anti-ship missiles attacking in quick succession, the defender's cycle time is highly compressed, which makes a defense against a "stream raid" more difficult even with an autonomous weapon such as the RIM-116A.

Attempts to counter this vicious cycle with conventional missile developments are unlikely to succeed because the same technologies that improve the speed, agility, and response time of the defender's missiles are just as likely to improve the attacker's performance. By using directed energy systems, the defender has a speed advantage on the order of roughly six orders of magnitude to reduce the "time of flight" required to reach the approaching missile. In the 2-5 seconds required to deposit laser energy on a target, a Mach 4.0 missile will travel only about 3.5 nautical miles. Given a sufficiently powerful laser in this scenario, the attacker could be destroyed at 16-18 nautical miles from the defending platform, which is more than twice the best distance attained with conventional systems.[105]

As previously discussed, air breakdown will generally limit ultra-wideband microwave systems to shorter ranges than laser systems. However, microwave systems still enjoy a significant speed advantage over conventional missiles. In addition, the typical maximum dwell time that is necessary to produce disruptions within the guidance package of the attacking missile is on the order of 600 milliseconds or less.

Unfortunately, drastically reducing the "time of flight" for directed energy does not eliminate the requirements for detection, acquisition, and identification. These processes dominate the engagement sequence for a directed energy system. Unless mechanically scanned surveillance systems, such as the SPS-48E, are replaced with fixed planar arrays, the defender may lose 3-4 miles of the battle space before it has the first opportunity to detect the target.[106] This time is critical in the case of cruise missiles that have dramatically reduced signatures. While laser trackers and other electro-optical devices will produce marginal improvements in acquisition and tracking times, each has vulnerabilities to environmental factors. Nevertheless, the fact that directed energy weapons reduce the "time of flight" gives the defender that much more time to detect, identify, and engage the target.

Anti-aircraft Defense

Cruise missiles approaching a ship typically leave little doubt as to hostile intent. However, aircraft are more problematic. There may be a significant number of so-called aircraft, which are neither friend nor foe, but operate within the battle space, which explains why "track identification" is critical in such situations. During flight operations, aircraft carriers have the additional challenge of distinguishing between hostile and friendly aircraft. Electronic identification systems are of some help, although no electronic

system fully addresses the problems of cryptographic compromise and battle damage. The drastic reduction in "time of flight" of directed energy systems allows a more rigorous identification process to be employed, and thereby decreases the probability of fratricide.

Hostile tactical aircraft carrying laser guided munitions or short-range air-to-surface rockets are generally a lesser-included case in the air defense problem. The preferred means of engaging tactical aircraft is likely to be other tactical aircraft, given the latter's ability to obtain a visual or multi-sensor confirmation of the target's identity at far greater ranges than any surface based sensor.

While tactical aircraft are subject to destruction in much the same fashion as cruise missiles, there are some substantive differences. For example, the destruction of the radome of a tactical aircraft is likely to have little impact on its aerodynamic survivability. In fact, its destruction may not diminish the effectiveness of air launched anti-ship missiles that are equipped with active seekers. On the other hand, the aircraft's control surfaces, fuel tanks, and weapons stores offer a variety of aim points, even when approaching the ship head-on. If environmental conditions permit, the laser is likely to be the weapon of choice. Its ability to precisely track the target and its short "time of flight" minimize the risk of fratricide. It also provides the options for engaging missiles at long-ranges, which means that the defender may be able to fire fewer weapons and thereby slow the rate at which the ship's magazine is depleted. As a back up, the Rolling Airframe Missile provides an all-weather capability for aircraft engagement.

Microwave systems, as with the CIWS that they would replace, are the least desirable option for anti-aircraft defense. Shipboard ultra-wideband microwave systems are not likely to have lethal effects for two reasons. First, an aircraft that fires a short-range tactical missile or lofts a laser-guided bomb will likely remain outside the range of an UWB device. Second, manned aircraft tend to incorporate far more robust and redundant control systems than unmanned missiles. It would require the near simultaneous disruption of two or more independent flight control computers to adversely affect an aircraft with a typical digital flight control system. The effects of microwave defensive systems are likely to be far more subtle. The most vulnerable systems are those with antennas, such as those that support communication and sensor systems.

The disruption and degradation of aircraft sensors and mission computers will make it more difficult for enemy pilots to attack the carrier successfully. The more sophisticated the aircraft, the greater the probability that the

mission computer will control the essential sub-systems. For example, seekers on externally carried stores are particularly vulnerable to disruption. To preclude inadvertent destruction of the launch platform, most air-launched missiles are required to pass an internal self-test before it will accept a launch enable signal. Any disturbance of the missile guidance and control circuitry may be sufficient to preclude the release of the weapon. With the exception of fixed-fin, forward firing rockets and so-called “dumb iron bombs,” any weapon is subject to the same type of microwave effects that a cruise missile will encounter in the terminal phase. Microwave systems may also offer a limited defense against unguided ballistic weapons, such as bombs and rockets, by damaging the fusing mechanism or causing premature detonation.

Directed energy weapons would provide an enhanced capability against the category of aircraft that are known as “low, slow flyers.” This typically includes light civil aircraft, ultra-lights, and helicopters that are characterized by relatively low speeds (less than 300 knots), low infrared signatures, and few if any distinctive electronic emissions.[107] If environmental conditions permit, the laser provides the system of choice. An integrated laser tracker, such as the Sea Lite Beam Director, can provide an image of the target at long range. In the past, light aircraft and helicopters have exploited their small size to obtain a visual identification of the carrier or other high value units before they could be positively identified. The laser director-tracker shifts the advantage back to the surface ship, because once the target is positively identified as hostile the laser can destroy it before the target can approach friendly units.

If the target’s identity cannot be determined, or if the rules of engagement preclude its destruction at long range, the ultra-wideband microwave system has a high probability of successfully engaging the target in the terminal phase. The propulsion systems of light civil aircraft and ultra-lights are particularly vulnerable to disruption. If the aircraft is being used in a kamikaze role, there is the additional possibility that the use of UWB microwave weapons could cause the premature detonation of its explosive cargo.

Military helicopters are another problem. While lightly armed reconnaissance helicopters, without anti-ship missiles, may be countered in the same manner as other low, slow flyers, those equipped with anti-ship cruise missiles pose a threat similar to tactical aircraft. Fortunately, when configured with missiles, the tactical ranges of helicopters are generally limited and, if based ashore, are unlikely to reach carriers that are operating 100-150 nauti-

cal miles off the coast. Nevertheless, this threat must be considered. For a helicopter to employ its weapons at their optimum ranges, it must identify the target vessel by some means. Unless it has third party targeting, the helicopter will have to enter the ship's "surveillance volume," which provides an opportunity for the defender to detect and identify the helicopter. Once again, if environmental conditions permit, the laser system offers the optimum combination for long-range identification and rapid engagement. Otherwise, the engagement options are the same as for tactical aircraft.

Anti-Surface Ship Options

The aircraft carrier must also be able to defend itself against hostile surface craft. While the primary means of destroying enemy combatants is generally anti-ship missiles and other guided munitions launched from carrier based aircraft, every high value unit needs a method of self-defense that is not constrained by flight operations. The *Seasparrow* has a limited anti-ship capability.[108] The potential effectiveness of the RIM-116A in a counter-surface mode is unknown, but the relatively small size of the warhead (25 lbs) is likely to be a limiting factor.[109] While the addition of directed energy systems is unlikely to produce a mechanism for directly engaging surface combatants, there may be new opportunities for neutralizing such threats with non-lethal measures. As with air defense, one of the greatest advantages of a laser director-tracker is its ability to illuminate and visually identify targets at long range.

Non-lethal Capabilities

Directed energy offers the potential to disrupt the sensors of a surface combatant at the maximum line of sight. The rapid responsiveness of directed energy weapons makes them particularly useful against high-speed patrol boats or surface-effect craft that can effectively out-maneuver the harassing fire of conventional gun systems.[110] The physical characteristics of directed energy systems give the defender greater control over the effects generated than any conventional weapon. Lasers have the ability to travel great distances, and the narrow beam and excellent beam control provides a high degree of certainty that the energy will be deposited on the target. Ultra-wideband microwave systems have a broader beam (on the order of one degree), but are limited in range by the upper limits imposed by the atmospheric breakdown that occurs at higher power levels. Both systems can be

employed in scenarios in which the risk of collateral damage or that the energy could be traced back to the ship would preclude the firing of conventional weapons.

Anti-Fast Patrol Boat Operations. While the destruction of radomes, antennas, and waveguides can render enemy radar unusable, electro-optical sensors are even more vulnerable than RF devices to laser destruction. Destructive techniques provide essentially the same level of protection as jamming without exposing the defender to attack by an anti-radiation missile. Unlike a jammer, the laser can be secured once the sensor is destroyed. The narrow beam of a laser weapon makes it less liable to counter-detection than a laser illuminator. Depending upon the characteristics of the laser and the sophistication of the techniques used, the opponent may not discern the cause of the sensor failure until it can examine the waveguide or antenna itself.[111] Given the lethal ranges of fast patrol boats, microwave systems may be able to do little more than disrupt sensitive electronic surveillance and communications systems.

Counter-terrorist Operations. On the other hand, small craft such as “boghammers” or “zodiacs,” that attempt to harass or attack the carrier may be neutralized by directed energy devices that are used for anti-personnel or anti-equipment purposes. Non-lethal options are particularly important when operating in areas where the use of conventional weapons may be precluded. For example, microwaves can neutralize the electrical systems of the attacker’s boats without creating an international incident because the potential terrorist would not have any tangible proof that defensive measures were taken.[112]

Submarine Defense. There is a theoretical possibility that a laser director-tracker could be used to detect and destroy submarine periscope sensors. If used for nothing else, it immediately places the submarine on the defensive because it sends an unambiguous message that the submarine has been detected and identified. As with other anti-submarine weapons, it is essential to ensure that friendly submarines are not mistakenly attacked. This concept, however, may not prove to be practical because the delay introduced by placing a human operator in the loop would assure that all but the least competent submariners would not be engaged.[113]

Counter-surveillance. Directed energy weapons add a new alternative for dealing with both hostile and third party reconnaissance systems. The same

counter-sensor capabilities that can be employed for air and surface defense can also be used to neutralize long-range surveillance systems. For example, a maritime patrol aircraft that is supporting third-party targeting for coastal anti-ship missile batteries could have its electro-optic sensors destroyed and its radar and communications systems disrupted. Similar techniques could be used to discourage surface vessels from functioning as intelligence collectors.[114] Ultimately, a ship-based laser system could be employed to disable surveillance from space-based platforms. Such a capability has broad tactical and strategic implications.

Directed Energy Options

The space, weight, power, and cooling requirements of directed energy technologies have a significant effect on the transition from engineering development to operational weapons. While the technological community has made impressive progress in recent years, both systems require large apertures to focus the transmitted energy as well as power distribution systems that are capable of providing megawatts of power. These physical constraints place a limit on the types of platforms that can be economically modified to accommodate them. While much of the historical work with directed energy systems focused on anti-ballistic missile applications, it is interesting to note that the employment of directed energy systems in a direct-fire, short-range, tactical air defense mode would simplify the challenges of detection, tracking, and power generation.

There are several possible ways to use directed energy to defend a ship. The purpose of this study is not to propose a definitive plan, but to establish a framework for understanding the potential capabilities and limitations of directed energy within which strategists and technologists can begin to assess the impact on "fleet tactics." As this study will argue, *Nimitz* class nuclear powered aircraft carriers (CVN) have a projected service life of over fifty years, and each carrier is scheduled for mid-life refueling and major overhaul at the 23-25 year point. As the largest naval vessels in the world, with dual nuclear power plants, these ships provide a viable option for the initial deployment of tactical directed energy systems.

As presently configured, *Nimitz* class CVN's employ a combination of NATO *Seasparrow* surface-to-air missiles and the Close-in-Weapon System (CIWS) Gatling gun for self-defense.[115] While both the CIWS and the *Seasparrow* systems have undergone numerous upgrades since they were developed in the 1970's, their continued effectiveness is of concern.[116] The

replacement of these systems with a new generation of self-defense hardware offers a way to ensure the survivability of the carrier in the face of more demanding threats. The current plan calls for the replacement of the CIWS with the RIM-116A Rolling Airframe Missile system and the possible replacement of the NATO *Seasparrow* System with the *Evolved Seasparrow*, if the latter ever comes to fruition.

This study considers four alternatives for integrating directed energy systems into the self-defense suite of an aircraft carrier. The first option involves the removal of the conventional gun and missile systems and their replacement with ultra-wideband microwave systems. The consensus, as expressed in the interim report of the DE-ATAC Study, is that in view of significant progress in high power microwave technology in the last decade, microwave systems offer the best option for an all-weather system. The two major concerns with this approach are the limited effective range of microwaves as a result of atmospheric breakdown at high powers and the inherent risks of depending on a single technology for a critical defensive system.

The second alternative is the replacement of existing systems with high-energy lasers. The deuterium fluoride laser is one of the more mature technologies that has undergone extensive testing under both the MIRACL and Nautilus programs. The high-energy laser has demonstrated that it has a capability against various tactical targets. The principal disadvantages of this approach are the laser’s susceptibility to environmental effects, and its potentially limited capability against certain head-on targets. In maritime operations, the primary defensive system must be able to function satisfactorily wherever the ship is operating. If it relied solely upon a high-energy laser system, the ship could be left defenseless for several days in the event of severe weather.

The third option is to replace existing systems with a combined suite of ultra-wideband microwave systems and high-energy lasers. Under suitable environmental conditions, the long-range capabilities of the laser would complement the short-range, all-weather capabilities of the microwave system. The unique advantage of this option is that both systems have essentially bottomless magazines, which eliminates the need to reload in combat.

The final alternative, similar to the third, combines both high-energy laser and ultra-wideband microwave systems, and includes a conventional surface-to-air missile capability. This combination provides a robust set of self-defense capabilities that will function under a number of operational and environmental conditions. As part of this option, the Rolling Airframe Missile system provides a proven system that minimizes the risks associated

with the incorporation of directed energy systems that are still in development. This study concludes that the fourth option provides the best alternative for a defensive suite that will meet the challenges of the first half of the twenty-first century. It provides the framework for this study's examination of these directed energy concepts. The recommended option calls for replacement of the existing self-defense suite with two laser tracker director systems, four ultra-wideband microwave arrays and three Rolling Airframe Missile (RIM-116A) launcher systems. With three NATO *Seasparrow* magazine launcher assemblies, six associated radar directors and four CIWS mounts, the present self-defense suite contributes substantially to the ship's topside weight.[117] The weight, space, and power budgets allocated to the existing defensive systems appear large enough to accommodate the directed energy systems under consideration.

The Rolling Airframe Missile is programmed to replace the current CIWS and *Seasparrow* systems.[118] Three Rolling Airframe Missile magazine launchers could replace the three *Seasparrow* magazine launchers and nearly triple the number of missiles available.[119] Already fielded on large amphibious assault ships such as the Wasp class, it complements directed energy systems under development with a capability that has been tested in world-wide naval operations. Equally important is the collaborative kill mechanism that exists when it is employed in conjunction with a high-energy laser.

The two laser tracker-directors could replace a pair of Seasparrow directors. Using an approach similar to the Sea Lite Beam Director and the Airborne Laser, each tracker-director would include a fully integrated system comprised of an infrared search sensor, high resolution telescope, acquisition tracker, track illuminator laser, fine grain tracker, and the weapon itself.[120] Locating the laser tracker-directors on the carrier's island structure maximizes the height of the laser aperture, keeps it out of the surface duct (thereby reducing attenuation due to moisture in the duct), and minimizes exposure to heavy sea spray.

All CIWS mounts would be removed and be replaced with electronically steered planar arrays for the ultra-wideband microwave systems. Large planar arrays have demonstrated their environmental tolerance in the AEGIS cruiser and guided missile destroyer applications. Installed immediately below the flight deck, the arrays would at approximately the same height above the sea surface as the radar arrays on the latter classes of ships, while still providing a degree of physical isolation from other communication and sensor systems. An electronically scanned planar array is the preferred

choice for minimizing response time and reducing mechanical complexity. However, if the development of a broadband planar array is not practical technologically, then the impulse radiating antenna, which has been demonstrated successfully by the Phillips Research Site, can be used. The current CIWS sponsons can provide satisfactory fields of view for mechanically steered, impulse radiating antennas. If one employs the same general arrangement as used in the current defensive systems, then redundant defensive coverage can be provided.

The *Nimitz* class CVN propulsion plant is designed to provide steam for the aircraft catapult launch systems, as well as routine propulsion requirements, and to do so with a single reactor. The dual reactor configuration provides a substantial power margin. With appropriate modifications to the ship's electrical power distribution system, the power demands for any foreseeable directed energy system could be met. Unlike terrestrial and airborne applications, a seaborne system has the advantage of being able to use seawater as a primary or secondary cooling medium. Using the current engineering models for aircraft carriers as a point of reference, a reasonable assumption is that these directed energy systems will not require any major structural redesigns. Given the sheer size and the margin of power available, the CVN is the best-suited warship to integrate the directed energy technologies that are under consideration.

This conservative approach permits the Navy to examine the capabilities of directed energy weapons while providing a more effective defensive system against advanced cruise missiles. It would also enable the Navy to assess the synergy between high-energy lasers systems and the Rolling Airframe Missile against sophisticated, high-energy missiles. This approach is consistent with the incremental introduction of using more advanced directed energy concepts, such as electro-magnetically-enhanced warheads for surface-to-air missiles, for protecting naval forces.

Summary

The incorporation of three separate defensive systems, each capable of providing 360-degree coverage, would improve the ability of aircraft carriers to defend themselves against multi-axis saturation attacks. Overlapping "fields of fire" and rapid re-engagement times will eliminate the vulnerability that exists at the seams where the coverage of defensive systems converge. The essentially bottomless magazines of the laser and microwave systems make stream raid tactics of dubious effectiveness.[121] The larger

magazine of the Rolling Airframe Missile launchers should require less frequent re-loading, and thus further reduce the vulnerability of the ship to stream raids. If re-loading operations can be deferred until there are more favorable environmental conditions, the laser system can provide long-range defense while the missile launcher is reloaded.[122] Not unexpectedly, there are natural synergies among the three weapon systems, as shown in Table 3.

If environmental conditions permit, the CVN will have the added capability of visually identifying aircraft or surface vessels with the optical sensors associated with high-energy lasers. Other possibilities include the integration of this sensor data to permit cueing of the Block 1 RIM-116A. Directed energy systems also offer a range of non-lethal options, ranging from blinding the sensors on surveillance aircraft to an anti-personnel capability against terrorist speedboats. The rapid response and potentially covert nature of directed energy systems makes them the weapon of choice in certain politically sensitive scenarios, such as the exercise of the right of innocent passage or while anchored within the territorial waters of another nation. A suite of high-energy lasers and radio frequency weapons when combined with a modest conventional surface-to-air-missile capability gives the CVN a more credible defensive capability across a broader range of threats than comparable suites of weapons.

Table 3. Complementary Weapons Matrix[123]

		UWB Microwave	HEL (RIM-116A)	RAM
Range	Head-on Threat	<.5 - 7 km	<5 km	.3 - 10 km
	Crossing THREAT		<15 km	
Aim point		Guidance system Flight controls Signal processor	Radome Control surfaces Warhead	Not Sensitive
Sustainability (numbers of shots per reload)		Essentially unlimited	Hundreds	21 (per launcher)
Threat Maneuvering/Speed		Not affected	Not affected	Challenged
Atmospheric Conditions		Minimal Sensitivity	Sensitive	Minimal Sensitivity
RF Countermeasures		Minimal Sensitivity	Not affected	Challenged
Low RCS		Minimal Sensitivity	Not affected	Sensitive
Crossing/Head-on Profile		Not affected	Easier/harder	Harder/easier

Source: Author.

VI. New Concepts for Employing Naval Forces

The legacy of the Second World War and the years confronting a "blue water" Soviet fleet has influenced how the U.S. Navy formulated its operational concepts for the twenty-first century. Naval expeditionary operations are based on the carrier battle group and an amphibious ready group. As Captain Wayne Hughes described in his classic *Fleet Tactics: Theory and Practice,* one of the principal naval lessons of the Pacific campaign of the Second World War was the need for defensive firepower. This led to the massing of carrier battle groups into the multi-carrier battle forces that remain the centerpiece of U.S. Navy operations more than fifty years later.[124]

During the cold war, the U.S. Navy and its NATO allies refined the concept of defense in depth to meet the ever-growing challenge from the Soviet fleet. Rings of fighter aircraft, AEGIS cruisers and destroyers, and ultimately point defense systems, such as the Seasparrow and Mark-15 CIWS, were employed to defend high-value units. When confronted with regimental raids of Badgers and Backfires, long range anti-ship missiles, such as the SS-N-12 and the SS-N-19, and the omnipresent submarine threat, it was expected that defending aircraft and escort ships would be lost. Regardless of the maneuver employed to reach the engagement, the outcome would have been determined by attrition, much as it was for Nelson almost two centuries years earlier.

As noted previously, Naval Doctrine Publication 1 emphasizes the importance of maneuver warfare, which it describes as the more preferable and effective approach to war.[125] While there have been lengthy discussions of whether naval warfare is inherently based on attrition, maneuver, or a hybrid of the two, the fact remains that current trends in both tactics and technology are oriented toward a layered defense for a multi-carrier task force.[126] The model today remains much as it was in the past in which maritime dominance is attained by establishing control of the sea through sweeping away one's opponents. The influence of Mahan, which relied on massing decisive firepower, seeking the enemy, and destroying him, remains strong. The question that must be asked is whether this is the best means to defeat the most likely threats that will emerge in the next thirty years.

Anticipating Opponent Behavior

The late John Boyd never wrote about naval warfare or fleet tactics, but his "A Discourse on Winning and Losing" offers several powerful ideas for naval thinkers.[127] Boyd examined land combat over the last three millennia in the context of Sun Tzu's philosophy of war. The result of his analysis was a synthesis of apparently disparate lines of thought into a model that describes the reasons for the successes achieved by non-traditional forces in the twentieth century.[128] It does not offer an explanation for the historic successes of the United States Navy, but it outlines a model that could be used by future adversaries to confront the United States. Boyd defined the critical elements of success as "variety, rapidity, harmony, and initiative."[129]

The trend in modern naval warfare in the twenty-first century, as previously noted, will likely involve states which seek to deny control of some portion of the sea to the powerful navies, whether at a critical choke point or in the waters adjacent to their coasts. Unwilling or incapable of making the investment needed to command the sea, these adversaries will rely on sophisticated, inexpensive weapons to raise the stakes against the expensive multi-purpose forces of the major powers. After confronting a global superpower at sea for a generation, there is a real danger of viewing naval operations against smaller states as a less significant enterprise. However, this assumption could prove to be a tragic miscalculation.

As Sir Julian Corbett observed almost 100 years ago, the strategy for a weaker opponent may be to deny the more powerful adversary the opportunity for a decisive battle. Enemy patrol boats hiding in fjords or caves can remain a "fleet in being" with little probability of being successfully engaged by conventional means. The dominant naval forces may never have the opportunity to annihilate the enemy's forces in a single crushing blow.[130] Instead, minor combatants may seek to engage in military actions under conditions in which an asymmetric exchange appears feasible. There are several historical precedents, including the Japanese success at the Battle of Tassafaronga in 1942 and the German successes against the Bergen convoy in 1917, both of which are exemplars of asymmetric attacks that produced devastating results.[131] The danger lies in the tendency to overlook these incidents and to dismiss them as "accidents of war."[132]

As an example, consider the havoc that four corvettes, each firing four supersonic anti-ship cruise missiles, could wreak on a carrier battle force. While perhaps only one missile might hit, the prospect of a single hit against

a major U.S. combatant or auxiliary could be sufficient to dissuade the United States from further action.[133] After the successful operation against Libya in 1986 and against Iraq in the 1991 Gulf War, it is unclear how the American public would react to losses on the scale that the British suffered during the Falklands conflict.

Toward Dispersed Tactics for Naval Forces

The solution to this challenge may be found in a fortuitous confluence of tactical and technological developments. The United States and its allies have the unique opportunity to use directed energy technologies, which are sufficiently mature, in the development of new "fleet tactics" for confronting the asymmetric naval opponent.[134] This does not imply that the U.S. Navy should abandon the lessons learned from the years of confronting a global naval power. On the contrary, the Navy must retain its ability to deal with potential competitors as well as those nations that are capable of matching its forces on a regional basis. Nonetheless, it is increasingly evident that there will be numerous situations in which a new approach will be needed if the United States is to defeat unconventional opponents.

Operational Maneuver From The Sea is developing a new doctrine and equipment to meet the challenges faced by classic amphibious operations.[135] Building on the MV-22 *Osprey*, the advanced Amphibious Assault Vehicle (AAAV), and an improved Landing Craft Air Cushion (LCAC), the Marine Corps is committed to the concepts of "ship to objective maneuver" and "over the horizon assault."[136] The result is that the doctrine of amphibious warfare has been fundamentally reshaped. In the future amphibious forces will no longer be constrained to a small set of beaches that are suitable for conventional landing craft. For supporting naval forces, the ability to remain at a significant distance offshore increases the freedom of movement, introduces uncertainty in the enemy's targeting, and provides opportunities for deception.[137] What is needed is a shift from classic battle group tactics toward the development of a new conceptual framework for carrier operations.

A traditional task force operating in a defensive screen presents a readily discernible pattern that an adversary can discover with spaced-based sensors as well as radar, acoustics, and electronic surveillance. The detection of a single battle group unit helps to orient the enemy's search, while the detection of additional units informs the adversary of the location of these high-value units. A more structured naval formation is more readily discernible.

Hughes was even more blunt, stating unequivocally, "a major consequence of massing for defense is the certainty that the enemy will be aware of the fleet and its general location."[138] The clustered defenders could become an opportune target because their very proximity hampers their ability to engage targets without fratricide.[139] In the historic confrontations between major battle fleets, escort vessels serving in the screen were, by necessity, expendable in the defense of the capitol ships. What may have been an acceptable risk in the past is no longer prudent in cases that do not involve vital U.S. interests.

The answer may lie in the use of a dispersed force that combines the inherent mobility of the carrier with a robust self-defense capability. Freed from the requirement to support amphibious operations within sight of land, the carrier gains a new opportunity to exploit its inherent speed, flexibility, and self-sufficiency. Instead of a classic battle group, a carrier and a nuclear powered submarine could operate in tandem. The two vessels make a natural pair that can optimally employ the mutual strengths of speed, reduced logistical needs, and the ability to dominate the air, surface and sub-surface environments. Freed from the slower moving escorts that require frequent refueling, the carrier can sustain comfortable cruising speeds of 20-25 knots on an indefinite basis. Capable of sprinting at higher dash speeds, the carrier has the ability to introduce substantial uncertainty in the calculations of those who seek to target it. Even when operating within a relatively small 90-degree sector at ranges of 100 to 150 nautical miles from an enemy's coast, the carrier is operating in an area greater than 10,000 square miles in which it must be found. The ability to create ambiguity and confound the enemy reduces the carrier's vulnerability to attack from both cruise missiles and theater ballistic missiles. And dispersion minimizes the risk that more than one unit would be exposed to chemical or biological attack.

The ability to exploit the inherent flexibility and mobility of naval forces will compel the adversary to fight on the defender's terms. An opponent that is forced to fight further out to sea increases the advantage to the United States and its allies.[140] Another advantage of a dispersed force is the fact that hostile surveillance units, when confronted with a single contact rather than a formation, must seek some additional confirmation of the identity of the unit. When the opponent is uncertain, it effectively shifts the advantage to the defender, which now gains more time to identify and destroy the attacker.

Sea-based aircraft will likely remain the most effective means for destroying hostile patrol craft and tactical aircraft at extended ranges. At those

times when the use of fixed or rotary wing aircraft is not possible, the defensive flexibility of directed energy weapons enhances the carrier's survivability. The inclusion of the advanced optical sensors that are associated with high-energy lasers will help to positively identify ships and aircraft within the battle space and do so at greater ranges, which further shifts the balance in favor of the defender.

As the U.S. Navy continues to shrink in size and increases the capabilities of individual units, there will be natural conflicts in the missions performed by these units. Consider, for example, the case of the AEGIS cruiser. During the Cold War, a cruiser was often assigned to the mission of terminal air defense of the carrier, but that mission is now an unaffordable luxury. In the next decade, that same cruiser is likely to have the role of power projection as a launch platform for Tomahawk cruise missiles, an air defense mission for protecting an amphibious force, and quite possibly a critical role in theater ballistic missile defense.[141] It is highly unlikely that any of these missions will be best performed by stationing the cruiser at a distance of 5000 yards from the carrier. The AEGIS guided missile destroyers, which are replacing earlier generations of guided missile frigates, share these missions as well as other duties, including maritime interception operations and commerce protection. Using sophisticated multi-mission surface combatants to form a defensive ring of steel around carriers reduces their theoretical capability in combat.

The danger is that the attempt to strike a compromise among the diverse missions performed by these naval platforms is likely to help the adversary pinpoint the location of the naval force. The reason is that each mission undertaken by units of a classic battle group imposes certain physical constraints on the group's location. The carrier must be within the combat radius of its aircraft to project airpower; the cruiser that launches land-attack cruise missiles must be within range if its missiles are to reach their targets; and the ballistic missile defender must be positioned along the likely trajectory of attacking missiles to intercept the targets. While individual missions may be accomplished while operating over hundreds or thousands of square miles, there is likely to be a relatively narrow area from which all of these missions can be accommodated simultaneously. By identifying all of the missions assigned to a battle group, an enemy can then define the probable location of the fleet and proceed to target it.

Dispersion also facilitates the use of deception. As observed by the classic Chinese strategist Sun Tzu, the target is the enemy's mind and if an enemy is confused, the only hope for success is luck. The goal is to present

one's foes with an image that they expect to see. The deception might be as simple as decoys that lead enemy aircraft to an AEGIS cruiser, or it might be as complex as a full-fledged amphibious feint. These are not new tactics, but are classic tools that become more effective when the force is no longer constrained to engage in set piece defensive arrangements.[142] Old tactics become more effective with technological advances. The combination of multi-spectral passive sensors, Block 1 Rolling Airframe Missiles with dual passive seekers, and high-energy lasers with low probability of intercept would strengthen the ability of the carrier to conduct flight operations without electronic emissions.[143] Armed with these tools, the carrier is no longer forced to choose between covert operations and robust defense.

The unmatched capability of the U.S. Navy to provide the logistics that are necessary for tactical flexibility has contributed to its success as the preeminent naval power. However, as the supporting logistics become more complex the naval force itself becomes more vulnerable. The nature of replenishment operations, which are highly structured events, is to establish operational patterns that can be discerned by an adversary. While ships replenishing at sea can maneuver, changes in course and speed must be carefully executed. If attacked, the replenishing force is limited in the number of responses available and the speed with which they can be executed.[144]

The conceptual basis behind the U.S. Navy's attempt to build nuclear-powered carrier task forces during the 1960's was the principle that a self-contained combat force is more agile and better able to seize the initiative. While this proved financially challenging, it has strengthened the reasons for minimizing the requirement that carriers refuel their escorts at sea.

A self-defense suite that includes directed energy weapons will allow the carrier battle force to enjoy the defensive advantages of dispersion, while exercising its unique ability to concentrate offensive naval striking power.[145] The combination of fixed wing aircraft, helicopters, and unmanned air vehicles in a dispersed force can keep the adversary off-balance because it can strike from multiple axes with no apparent pattern. By appearing simultaneously over a number of targets, the combat aircraft on the carrier can put pressure on the adversary and thereby introduce confusion. Sea-based air power gives the U.S. Navy an unmatched ability to defeat its enemies.[146]

Anticipating Countermeasures

An inevitable law of military history is that each new weapon has been met with countermeasures. It is likely that the development of directed energy weapons will be governed by that same law. For example, ablative coatings and RF hardening may reduce the vulnerability of conventional weapons to the effects of lasers and microwave devices, respectively. While some degree of RF hardening could be accomplished with minimal penalties, the trend in modern microprocessor electronics is to build the most economical and efficient devices, but these are also the most vulnerable.[147] Those charged with designing modern naval weapons will be confronted with the classic choice between survivability and efficiency.

Similarly, anti-laser measures, including the use of ablative coatings on missiles, increase the weight and hence drag of the missiles, while reflective surfaces tend to increase the electro-optical signature, and thereby simplify the ability of the defender to detect missiles. There are detection systems that will warn an aircraft that it is being illuminating by a laser, but it is difficult to detect a narrowly focused beam from a laser weapon at short ranges.

Eventually, other nations will field weapons that operate at the speed of light. As with nuclear weapons, directed energy systems will favor those who initiate the attack. The large apertures that give lasers high power and directional control have the greatest inherent vulnerability to attack. There will be pressure on the belligerent to fire the first salvo in order to blind the opponent.[148] A less sophisticated opponent might choose to blind directed energy systems with the electromagnetic pulse of a nuclear detonation, but this action would cross the nuclear threshold and run the risk of nuclear war. A more likely scenario would be the employment of explosively driven RF munitions to blind the sensors associated with high-energy laser and RF systems. However, the relatively short ranges of ultra-wideband sources suggest that an attacker must use some type of delivery system. The implication is that tactical aircraft, unmanned air vehicles, or missiles that are used as delivery systems would be subject to attack by the very systems that they are intended to destroy. The defender, using directional antennas, enjoys a physical advantage over an attacker that uses an explosively driven source to radiate energy in a near spherical pattern. The reason is that the focused beam of a large aperture system delivers maximum power with minimal energy losses. The defender's advantage may be strengthened by

the development of more sophisticated modulation schemes that extend the engagement ranges by enhancing the disruptive effects attained at lower radiated powers.[149]

As with most weapon systems, the advantage is likely to shift successively from the attacker to the defender, and back again, as directed energy weapons experience technological and operational advances. Regardless of whether the United States develops these capabilities, it is likely that other states will perfect weapons that are ideally suited for the disruption and destruction of the information systems upon which modern naval forces depend. As the information centric concept of military operations gains ascendancy in military thinking, it will create a disproportionately greater vulnerability to attack from directed energy weapons.[150]

Understanding Potential Anti-Satellite Applications

The introduction of directed energy weapons into naval forces raises the question of whether these systems could be designed for anti-satellite operations. While there are significant technical differences between anti-satellite and anti-cruise missile systems, the development of a dual-use system is feasible.[151] For example, the potential role of the MIRACL laser as a anti-satellite weapon sparked serious congressional concerns, and led the United States Senate to block any MIRACL testing that could be construed as an anti-satellite capability.[152]

While the ability to blind space-based sensors would have great tactical utility, the political and legal implications of deploying such system are unanswered. It is inevitable that the use of a sea-based anti-satellite system would be perceived as a strategic threat to other states, including Russia and China. The ability to neutralize enemy or third party space-based sensors would greatly enhance the survivability of U.S. naval forces and could prove particularly useful in protecting theater missile defense units. A blinded opponent would be forced to rely on ships, aircraft, and unmanned air vehicles, all of which are vulnerable to conventional defenses. It must be understood that any tactical advantage gained by having anti-satellite capabilities on naval forces would quickly disappear if the enemy responded with a strategic attack against the United States because it faced the prospect of losing the space-based sensors upon which its ballistic missile force depends.

The future offers more tantalizing possibilities. Sea-based lasers could be integrated into a system with space-based mirrors to provide a widely dis-

persed, survivable means for preventing states from gaining access to space. This development would define sea-based lasers as a strategic system, and thus raise the question of whether adversaries will field space-based laser systems that are capable of attacking the sensors and communications systems upon which U.S. military forces depend.

The choice of fielding laser anti-satellite weapons is likely to be made by other states. For example, the Department of Defense's annual report to Congress on the Chinese military declared that the People's Republic "may possess the capability to damage, under specific conditions, optical sensors on satellites that are very vulnerable to lasers."[153] This capability is consistent with China's development of lasers for military applications. It is a fact that the physics tend to favor ground or sea-based systems with large apertures and virtually unlimited power sources. From a technical perspective, a tactical shipboard laser system would enable the United States to preserve the option of fielding a robust, mobile anti-satellite capability. The political question, however, remains subject to debate.

VII. Conclusions

This study examined the implications of directed energy systems for fleet defense in twenty-first century naval warfare. The United States is likely to remain committed to a national military strategy that embraces naval expeditionary warfare as a major component of its military capabilities. However, the ability to project naval power ashore will be increasingly difficult as potential adversaries gain access to sophisticated, low-cost weapons.

Drawing from the experiences of the Second World War and competition with the Soviet fleet during the Cold War, U.S. Navy remains an expeditionary force that is centered on the carrier battle group and its associated amphibious ready group. Current technological and tactical trends are oriented toward the concept of defense in depth. The implication is that when confronted with overwhelming U.S. naval superiority, most adversaries will not run the risk of defeat in battle by directly challenging a major naval power, but will instead seek to make the cost of sea control as prohibitively expensive as possible. With the development of advanced cruise missiles that will pose an economical and widely available weapon for most opponents that seek to attack a major naval power on an asymmetric basis, the U.S. Navy must develop new defensive systems and new approaches to battle group operations.

This study began with an examination of the current status of directed energy technology, and noted that there has been significant progress in both high-energy lasers and ultra-wideband microwave systems over the last decade. It is likely that these technologies will continue to be developed for military applications. The inherent advantages of weapons that travel at the speed of light and possess a virtually unlimited magazine are obvious. On the other hand, both laser and microwave technologies have fundamental physical limitations that limit their utility as autonomous weapon systems. For the foreseeable future, laser systems will be vulnerable to environmental degradation, while the range of microwave systems will be limited because of the atmospheric breakdown that occurs at higher power levels.

Among the microwave technologies examined, ultra-wideband systems are best suited to defensive applications when one considers the inherent difficulties of hardening missiles across a broad frequency band. The range advantages of narrow band, high-power microwave systems are overshadowed by the need for prior knowledge about the target and the ability of the adversary to protect this weapon.[154] While it is too early to identify the best

candidate for the high-energy laser system, this study used the Mid-Infrared Advanced Chemical Laser (MIRACL) as a basis for discussion because it represents a technology that can be fielded with some degree of confidence. Current development efforts in the areas as dispersion-less antennas and diode-pumped solid state lasers probably will further enhance the military effectiveness of directed energy systems.

This assessment of the current technology suggests that the operational deployment of directed energy systems in the 2020-2025 timeframe is both feasible and prudent. Two *Nimitz* class nuclear powered aircraft carriers, *John C. Stennis* and *Harry S. Truman*, will require upgrades to their defensive suites, in conjunction with the mid-life re-fueling that is scheduled for the second decade of the next century. The timing of these events provides a window of opportunity for integrating directed energy systems into the carrier force. With the physical size and the margin of power available on nuclear-powered aircraft carriers, these naval vessels are well suited to accommodate the directed energy systems that are likely to be available.

This study examined four possible configurations for integrating directed energy systems into aircraft carriers. The first two included the replacement of the carrier's existing NATO *Seasparrow* and Mark 15 Close in Weapons Systems with either an ultra-wideband microwave system or a high-energy laser. The third alternative combines laser and microwave systems. The fourth option, which this study finds most preferable, involves a combination of ultra-wideband microwave systems with a set of high-energy lasers and three Rolling Airframe Missile systems.

This composite suite is advantageous because it offers a robust self-defense capability that exploits the operational synergies of these systems. The addition of "speed of light" weapons gives the defender with the ability to break the vicious cycle of ever-faster missiles. These directed energy systems would also provide a number of non-lethal options for self-defense. Freed from the need for a layered defensive screen of ships, the nuclear powered carrier, operating in tandem with a nuclear powered submarine, could exploit its inherent speed and self-sufficiency to deny its adversaries an opportunity for conducting asymmetric attacks. By dispersing the battle group, each platform could choose the optimum location for its primary mission of launching cruise missiles, defending against theater missiles, protecting commerce, or maritime interdiction. This flexibility will become increasingly important as the Navy moves to a smaller and more capable force that operates in the littoral region close to the shore.

The development of sea-based high-energy lasers raises the possibility of a strategic anti-satellite capability. While there are significant political issues to be resolved, there is evidence that other nations are developing equivalent capabilities today. As long as the United States possesses the most information dependent military force in the world, it will be vulnerable to states that use directed energy to disrupt or destroy its information dominance. The failure to develop and field directed energy systems could weaken the ability of the U.S. Navy to provide the naval presence and military power upon which the United States has depended throughout its history.

Recommendations

This study concludes with several recommendations for the U.S. defense establishment as it considers the role of directed energy weapons in its military forces.

First, it is essential for the United States to conduct a detailed study of the critical milestones that affect the incorporation of directed energy systems into *Nimitz* class nuclear-powered aircraft carriers. By doing so, the U.S. Navy and the Department of Defense would have the opportunity to identify the critical technological constraints that will affect the development of this weapon. Officials in the defense establishment are well aware that the technology developed during the next ten years will define the systems that will be available for the first half of the next century.

Second, it is equally essential for the United States to continue its current efforts to develop both microwave and laser systems. If the United States is to maximize the benefits of implementing directed energy technology, it is likely that defensive suites for aircraft carriers will rely on directed energy weapons and conventional missiles. Both will be necessary to permit the carrier to operate without escorts. To meet that objective, a suite that includes ultra-wideband microwave systems, high-energy lasers, and an advanced surface to air missile system will have significant operational advantages.

Third, it is essential for the U.S. Navy to collaborate with technological programs being conducted by the other military departments, including the Air Force's Airborne Laser and the Army's Tactical High-energy Laser. This collaboration will help to resolve issues of common concern, including questions about the thermal blooming of laser energy, the sensitivity of la-

sers to weather conditions, and techniques for overcoming the atmospheric breakdown that occurs with high power microwave transmissions.

Finally, in an era of constrained resources, the Navy must seek the best ways to use the nation's technological strengths to ensure that U.S. expeditionary forces are capable of meeting the threats that will emerge in the twenty-first century. The broad strategic conclusion of this study is that directed energy weapons are among those critical technologies that will help the U.S. Navy defend the vital interests of the United States on the oceans of the world.

Notes

1. For a discussion of contemporary views on the implications of the information dominated environment, see Joseph S. Nye and William A. Owens, "America's Information Edge," *Foreign Affairs*, Vol. 75, No. 2, March/April 1996, 20-36. See also Department of the Air Force, *Cornerstones of Information Warfare*, 1997, May 9, 1999, http://www.af.mil/lib/corner.html.

2. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century*, Directed Energy Volume (Washington, DC: USAF Scientific Advisory Board, September 1996).

3. Naval Studies Board, National Research Council, *Technology for the United States Navy and Marine Corps, 2000-2035—Becoming a 21st Century Force* (Washington, DC: National Academy Press, 1997), pp. 183-187.

4. The American Physical Society cited the uncertainty and differences of opinion surrounding the potential effectiveness of directed energy weapons when it established a study group in 1983. The group's report, published in April 1987, documents many of the unexpected challenges that confronted technologists who attempted to develop operational laser systems. See *Science and Technology of Directed Energy Weapons*, *Report of the American Physical Society* (New York, NY: American Physical Society, April 1987), pp. 53-129. The history of the U.S. Air Force's efforts to develop laser weapon systems is ably described in Robert W. Duffner, *Airborne Laser: Bullets of Light* (New York, NY: Plenum Press, 1997), pp. 5-93. Other service attempts as well as a West German effort are described in Major General Bengt Anderberg and Myron L. Wolbarsht, *Laser Weapons: The Dawn of a New Military Age* (New York, NY: Plenum Press, 1992), pp. 121-136.

5. A more appropriate model for the adaptation of lasers might well have been the evolution of Robert Goddard's fledging rockets of the 1920's into the ICBM's of the 1950's. It took a full thirty years for rocket technology to mature, notwithstanding substantial investments by both sides during World War II.

6. US General Accounting Office Report, *Navy's Aircraft Carrier Program: Investment Strategy Options*, GAO/NSIAD-95-17, August 27, 1998, http://www.fas.org/man/gao/gao9517.htm.

7. Captain Wayne P. Hughes, Jr. USN, Ret., *Fleet Tactics* (Annapolis, MD: Naval Institute Press, 1986), p. 205. For a full discussion of the challenges faced by Admiral Sims, see Elting E. Morison, *Admiral Sims and the Modern American Navy* (Boston, MA: Houghton Mifflin Co. 1942), pp. 106-147.

8. Bernard Brodie, *Seapower in the Machine Age* (1969; reprint, Princeton, NJ: Princeton University Press, 1943), p. 438. Brodie traces this caution back to historical figures such as Sir Robert Peel and Samuel Johnson. Furthermore, In this spirit, one does well to remember Captain Wayne Hughes' caution: "Usually more than one piece

of technology is required to create a revolution. Sail and canon together replaced the oared galley. Steam power alone was not enough to replace the ship of the line. It took the steam engine, the screw propeller, and the metal hull all together, which in turn made possible the big gun and the marriage of rifling, breech loading, and an effective fire control system . . . Great transitions require the engineering insight to fuse several scientific potentialities into a dramatically different weapon or sensor, the tactical insight to see how the weapon will change the face of battle, and the executive leadership to pluck the flower of opportunity from the thorns of government. The inspiration for these transitions often come from outside a navy. The perspiration always comes from within it." See Hughes, pp. 221 and 215.

9. See inter alia, Bill Hillaby, "Directed Energy Weapons Development and Potential" National Network News, July 1997, August 12, 1998, http://www.sfu.ca/dann/nn4-3_12.htm; Department of the Navy, *Challenges to Naval Expeditionary Warfare* (Washington, D.C.: Office of Naval Intelligence, March 1997), p. 15.

10. Department of the Navy, *Forward . . . From the Sea*, March 1997, July 10, 1998, http:www.chinfo.navy.mil/palib/policy/fromsea/ffseanoc.html.

11. Joint Pub 1-02, *DOD Dictionary*, December 1997, p. 172.

12. ADM Jay L. Johnson, USN, "Forward . . . From the Sea, The Navy Operational Concept," March 1997, http://www.chinfo.navy.mil/navpalib/policy/fromsea/ffseanoc.html.

13. *Joint Vision 2010*, p. 4.

14. *Challenges to Naval Expeditionary Warfare*, p. 6.

15. Headquarters, U.S. Marine Corps, *Concepts and Issues '98*, "Building a Corps for the 21st Century" (Washington, DC: 1998), pp. 32-33.

16. National Research Council, *The Navy and Marine Corps in Regional Conflict in the 21st Century* (Washington, D.C.: National Academy Press, 1996), pp. 35-36.

17. Department of the Navy, *Vision-Presence-Power A Program Guide for the U.S. Navy*, 1998 edition (Washington, DC: Office of the Chief of Naval Operations, May 1998), pp. 60-61. To meet this challenge, the Navy must develop the "doctrine and tactics that make sense in a new strategic environment, and . . . fund the necessary force structure that gives the naval expeditionary forces the most decisive impact for the least cost and at minimum risk, and thereby ensure operational primacy is sustained." See *Vision-Presence-Power*, p. 43.

18. The term "cruise missiles" is describes a category of air, surface or sub-surface launched unmanned air vehicles that rely upon relatively sophisticated guidance systems and sustained propulsion systems to reach their targets. The propulsion systems include turbofan, turbojet, rocket and ramjet propulsion systems with speeds ranging from high subsonic to supersonic. However, the distinction between cruise missiles and remotely piloted vehicles is growing increasingly less clear. See David J. Nicholls,

Cruise Missiles and Modern War: Strategic and Technological Implications (Maxwell AFB, AL: Center for Strategy and Technology, Occasional Paper No. 13) forthcoming.

19. The following summarizes the known producers and exporters of cruise missiles:

Cruise Missile Producers and Exporters

Argentina	India (poss. exports)	Japan	Sweden (exports)
Brazil	Iran	N. Korea (exports)	Taiwan
China (exports)	Iraq	Norway (exports)	U.K. (exports)
France (exports)	Israel (exports)	Russia (exports)	U.S. (exports)
Germany	Italy (exports)	S. Africa (exports)	

Note: Indonesia, Singapore, and Ukraine are also assessed to have the aerospace industrial capacity to produce cruise missiles. See "Cruise Missile Capabilities and Suppliers," Centre for Defence and International Security Studies, October 8, 1998, http://www.cdiss.org/tabanaly.htm.

20. *Ibid*.

21. "Challenges to Expeditionary Naval Warfare," pp. 12-13.

22. "Missile Capabilities by Country," Centre for Defence and International Security Studies, October 8, 1998, http://www.cdiss.org/tablef.htm.

23. "Cruise Missiles and WMD," Centre for Defence and International Security Studies, October 8, 1998, http://www.cdiss.org/cbwcm.htm.

24. "Selected RPV Capabilities," Centre for Defence and International Security Studies, October 8, 1998, http://www.cdiss.org/tablef.htm.

25. "Ballistic Missiles and WMD," Centre for Defence and International Security Studies, Internet, October 8, 1998, http://www.ediss.org/cbwbml.htm.

26. "Challenges to Expeditionary Naval Warfare," pp. 16-17.

27. "Ballistic Missiles and WMD," and "The Devil's Brews: An Introduction," Centre for Defence and International Security Studies, October 8, 1998, http://www.cdiss.org/cbwintro.htm.

28. Department of Defense, *Persian Gulf War Study* (Washington, DC: 1992).

29. General Sir Peter de la Billiere, *Storm Command—A Personal Account of the Gulf War* (London, UK: Harpers Collins Publishers, 1992), p. 148.

30. "Challenges to Expeditionary Naval Warfare," pp. 8-11.

31. "Challenges to Expeditionary Naval Warfare," pp. 22-23.

32. Lieutenant Commander J. Todd Black, U.S. Navy, "Commercial Satellites-Future Threats or Allies?" *Naval War College Review*, Winter 1999, November 19, 1998, http://www.nwc.navy.mil/press/Review/1999/winter/art5-w99.htm.

33. See Statement of Ira W. Merritt, Chief Concepts Identification and Applications Analysis Division, U.S. Army Space and Missile Defense Command, in "Proliferation and Significance of Radio Frequency Weapons Technology," Testimony before the Joint Economic Committee, U.S. Congress (Washington, D.C.: February 25, 1998) August 27, 1998, http://www.fas.org/irp/congress/1998_hr/s980225m.htm.

34. In other testimony before the committee, it was pointed out that an Australian professor, formerly associated with the Royal Australian Air Force, operates a personal web site that provides the basic guidelines for weaponizing a transient electromagnetic device. See Statement of Mr. David Schriner, Chief Scientist, Directed Energy Technologies, Schriner Engineering, in "The Design and Fabrication of a Damage Inflicting RF Weapon by "Back Yard" Methods," Testimony before the Joint Economic Committee, U.S. Congress (Washington, D.C. February 25, 1998) August 27, 1998, http://www.fas.org/irp/congress/1998_hr/s980225ds.htm.

35.Carlo Kopp, "The E-Bomb—a Weapon of Electrical Mass Destruction," *Infowar.com and Interpact, Inc*., October 9, 1998, http://www.infowar.com/mil_c4i/mil_c4i8.html-ssi.

36. Hillaby, "Directed Energy Weapons Development and Potential."

37. In 1995, North China Industries Corporation offered the ZM-87 anti-personnel weapon for sale, which is capable of causing flash blindness at ranges up to 10 km and permanent blindness at ranges of 2-3 km. See "Challenges to Expeditionary Naval Warfare," 15.

38. "Challenges to Expeditionary Naval Warfare," p. 15.

39. *Los Angeles Times*, November 28, 1998, quoted in AFSPC Legislative Liaison, December 10, 1998.

40. Ji Shifan, *Development of Tactical Air Defense Laser Weapons at Home and Abroad: An Outline*, trans. Leo Kanner Associates (Wright-Patterson Air Force Base, OH: National Air Intelligence Center, 1996), pp. 10-15.

41. H. H. Arnold and Ira C. Eaker, *This Flying Game* (New York, NY, 1938), pp. 130, 135-139.

42. N*ew York Times*, October 12, 1945, p. 1. and Bernard Brodie, "The Atomic Bomb and American Security," Institute for International Studies Memorandum No. 18 (New Haven, CT: Yale Institute for International Studies, November 1, 1945), p. 6.

43. Jeff Hecht, *The Laser Guidebook* (New York, NY: McGraw-Hill, Inc. 1992), p. 16.

44. Robert W. Duffner, *Airborne Laser: Bullets of Light* (New York, NY: Plenum Press, 1997), pp. 1-15.

45. Electromagnetic radiation is emitted when an electron transitions from a higher energy state to a lower energy state. A common example is the fluorescent light. It can also occur when there are changes in the rotational or vibrational states of molecules. In

quantum mechanics the smallest packet of light energy as a photon whose energy is determined by the difference between the initial and final energy levels. Planck's constant relates the frequency of the light to the energy of the photon:

$$E=h \times v$$

This, in turn, describes the wavelength of the light emitted. Emissions range from X-rays through the optical region into the infrared portion of the spectrum. When energy is added to the atoms in the lazed material, many of the electrons are excited to a higher energy level. Because it is an inherently unstable condition, the electrons will eventually fall back to lower energy states, or "decay." This occurs spontaneously, which results in the emission of randomly directed photons. Rather than returning to their ground states, electrons often decay to an intermediate energy level, a meta-stable state, where they may remain for microseconds. This phenomenon of electrons occupying higher energy levels is known as population inversion. A chain reaction can develop as photon emission is stimulated by collisions with other photons. This process results in release of photons travelling in the same direction, in phase, at the same wavelength. See Robert Aldrich, "Laser Fundamentals," NSWC, Dahlgren Division, August 27, 1998,: http://www.fas.org/man/dod-101/navy/docs/laser/fundamentals.htm.

46. Major General Bengt Anderberg and Myron L. Wolbarsht, *Laser Weapons: The Dawn of a New Military Age* (New York, NY: Plenum Press, 1992), pp. 11-42.

47. Richard Saunders, et al., *Lasers Operation, Equipment, Application, and Design* (New York, NY. McGraw-Hill Book Company, 1980), p. 10. For reference, The lower limit on the divergence (or spreading) of a laser beam is a function of the wavelength of the light and the size of the aperture. And divergence can be reduced by either shifting to shorter wavelengths (higher frequencies) or increasing the size of the aperture. Lasers whose divergence is reduced to the theoretical minimum are categorized as diffraction limited.

48. The causes of broadening include nearly adjacent transition energy levels, doppler broadening in gas lasers, and lattice vibrations in solid lasers.

49. Hecht, pp. 23-47, 263-272.

50. Hecht, p. 97.

51. USAF Scientific Advisory Board, pp. 32-33.

52. USAF Scientific Advisory Board, pp. 34-35, 49-51.

53. USAF Scientific Advisory Board, pp. 66-67.

54. In a device similar to a rocket engine, ethylene (C_2H_4) is combined with an oxidizer, nitrogen trifluoride (NF_3) and excited fluorine atoms are released as a product of combustion. Molecular hydrogen or deuterium is then injected with the atomic fluorine to produce an excited halide. See John Pike, "Mid-Infrared Advanced Chemical Laser (MIRACL)," *FAS Space Policy Project*, March 21, 1998, 1-4; August 27, 1998, http://www.fas.org/spp/military/program/asat/miracl.htm.

55. "Nautilus - Lasers are Lethal," U.S. Army Space and Missile Defense Command, October 3l, 1998, http://www.smdc.army.mil/NAUT.HTML. "Tactical High Energy Laser (THEL)," U.S. Army Space and Missile Defense Command, October 31, 1998, http://www.smdc.army.mil/THEL.HTML. Additional information is available from TRW Inc. at http://www.trw.com.

56. Pike, pp. 3-4.

57. Pike, pp. 3-4. A "contingency anti-satellite operational capability" was established in 1990. However, public disclosure came almost seven years later. See Joung R. Cook, "US Navy HEL Weapons Fundamental Issues," Address to the First Directed Energy Symposium, Kirtland AFB, NM, November 6, 1998. A discussion of the politics associated with the MIRACL system's potential as an anti-satellite weapon can be found in *Inside the Army*, November 30, 1998, slides 13-17.

58. Cook, slides 5-7.

59. For reference, the COIL uses a process that transfers energy from excited oxygen molecules to iodine atoms, and by using iodine atoms for the laser output, produces a wavelength of 1.3 microns.

60. US General Accounting Office Report, *Theater Missile Defense: Significant Challenges Face the Airborne Laser Program*, GAO/NSIAD-98-37, August 27, 1998, http://www.fas.org/spp/starwars/gao/nsiad98037.htm.

61. USAF Scientific Advisory Board, pp. 38-40.

62. Anderberg and Wolbarsht, pp. 38-39.

63. The term "ubitron" is derived from undulated beam interaction, which describes how the device uses a periodic transverse magnetic field known as a "wiggler" to cause a ponderomotive (beat) wave to develop. The period of the magnetic wiggler is then adjusted to produce a resonance between the beam and the ponderomotive wave. See "High Power Coaxial Ubitron Oscillator," DoD Multidisciplinary University Research Initiative, October 31, 1998, http://tempest.ece.ucdavis.edu/muri/western/ucd/adam/coaxosec.html.

64. Naval Studies Board, pp. 184-185.

65. Alternatives include passive wavefront correction using non-degenerate four wave mixing or stimulated thermal scattering for non-linear wavefront correction.

66. USAF Scientific Advisory Board, pp. 4-5, 40-47, 63-69.

67. Duffner, 239-253 and 271-305. The complexities of developing an effective tracking scheme are well documented in the history of the ALL.

68. Cook, slide 5.

69. The distribution of energy is caused by the Heisenberg uncertainty principle, molecular collisions, electric fields, magnetic fields, and Brownian motion.

70. Joseph S. Accetta and David L. Schumaker, eds., The Infrared and Electro-Optical Systems Handbook, vol. 2, *Atmospheric Propagation of Radiation* (Ann Arbor, MI: Environmental Research Institute of Michigan, 1993), pp. 3-64. While this text is the successor to *The Infrared Handbook*, chapters 4, 5, and 6 of the 1985 revised edition of the latter contains a wealth of empirical data on atmospheric absorption, scattering and propagation. The new text provides reference to both the HITRAN and LOWTRAN databases; however; it lacks some of the easily inspected graphs of the former. See William L. Wolfe and George J. Zissis, *The Infrared Handbook*, rev. ed. (Washington, DC: Office of Naval Research by the Infrared Information and Analysis Center, Environmental Research Institute of Michigan, 1985).

71. For example, carbon dioxide typically shows a seasonal variation, with maximum levels observed in early spring and minimum levels reached in late summer and fall.

72. The “clear blue sky” one observes overhead is due to molecular Rayleigh scattering, while the whitish gray haze observed at the horizon is due to aerosol effects. The haze may be caused by smoke, dust, or clouds. There is an overlap of effects when clouds, fog or smog form a portion of the haze. See Accetia and Schumaker, pp. 11-12, 100-112.

73. Accetta and Schumaker, pp. 11-12, 100-112.

74. Because convection heating typically dominates this phenomenon, a circular beam will generally be distorted into a non-symmetrical crescent shaped pattern that spreads transversely to the wind direction. See Accetta and Schumaker, pp. 290-297.

75. Samuel Glasstone, ed., *The Effects of Nuclear Weapons*, Air Force Pamphlet (AFP 136-1-3) (Washington, DC: Department of the Air Force, April 1962), and Samuel Glasstone and Philip J. Dolan, ed., *The Effects of Nuclear Weapons* (Washington, DC: Department of Defense and Department of Energy, 1977).

76. There was a simultaneous failure of 30 series of connected loops of streetlights on the island of Oahu. While the effects were little more than an annoyance, this event served to warn the United States military of the widespread secondary effects of electromagnetic pulses.

77. Glasstone and Dolan, pp. 514-529.

78. Merritt, pp. 1-2.

79. The effects of HPM devices can be categorized as follows: “Upset”—a temporary alteration of the electrical state of one ore more components, precluding normal operation until the radiation is terminated; “Lock-up”—a temporary alteration, as above, however, an electrical reset is necessary to restore normal operation after the radiation is terminated; “Latch-up”—an extreme form of lock-up that can result in either circuit destruction or pull down of power supply voltages; “Damage”—electrical destruction by a mechanism such as latch-up, metallization burn out or junction burn out. Since certain forms involve charge build-ups that decay over time, permanent dam-

age or electrical burn out is sometimes used to distinguish from the less permanent effects. See David M. Sowders, et al., *High Power Microwave (HPM) and Ultra-wideband (UWB): A Primer on High Power RF*, PL-TR-95-1111 (Kirtland AFB, NM: Air Force Material Command, 1995), pp. 81-84.

80. Semi-conductor devices will fail when exposed to voltages that exceed the dielectric strength of the component, or when RF induced current heats one of its subcomponents to its melting point. As Kopp points out, the trend towards equipment vulnerability is increasing. Voltage ratings for silicon bi-polar transistors typically vary from 15V-65V. Gallium Arsenide FETs are typically rated at about 10V. Dynamic Random Access Memories are typically rated at about 7V. Microprocessors are often rated even closer to their operating voltages of 3.3V to 5V.

81. Merritt, pp. 3-5.

82. Chemical explosives have energy densities on the order of 8kJ/cc. Present technology limits high-energy density capacitors to approximately 1J/cc.

83. The losses associated with the conversion of chemical energy into an explosion and the conversion of the magnetic energy into electrical energy could be avoided. As previously noted, explosive reactions represent a quite inefficient means of transferring energy.

84. Merritt, pp. 4-6. While there have been questions raised with regard to the reproducibility of some of the Russian claims. See L. L. Altgilbers, I. Merritt, M. Brown, J. Henderson, D. Holder, and Merriweather, *OCONUS Radio Frequency Munitions Test Report*, ATD-98-001, December 4, 1997. It is evident, from other systems that have been exported to the West, that Russian and other FSU laboratories continue to make major strides in this area.

85. In addition to switch limitations, the characteristic mismatch between the output impedance of inductive storage devices (1-10 ohms) and the high power RF systems operating typically between 10-100 ohms limits their efficiency. For capacitive systems, better dielectric materials are required so that less heat is developed during the charge/discharge process.

86. This includes the relativistic magnetron, an outgrowth of radar development; the large orbit gyrotron, a form of electron cyclotron maser; the relativistic klystron, which traces its origins to radar and weapons development; and the vircator, a relatively new and elegant design, that is commonly used in single pulse applications.

87. Schriner, p. 5.

88. The spark gap switch operates on the principle of creating an electrical breakdown within a dielectric material when the voltage reaches a set value. The high voltage stress placed on the dielectric material will form spark channels, which permits the current to flow. The violent breakdown process leaves debris in the current channels, which must be cleared prior to firing the switch again. Phillip's Laboratory has made significance progress in this area using gas switches that have demonstrated repetition rates of up to 1 kHz. See Sowders, *et al*., p. 46.

89. However, the penalty for a constant amplitude and phase response across a wide frequency range is a much lower gain than traditional narrowband antennas, which significantly limits the effective radiated power that could be achieved.

90. USAF Scientific Advisory Board, pp. 58-60. For an alternative view, see the U.S. Army forecast of Electronic Warfare/Directed Energy Weapons, http://mrmc-www.army.mil/mrmclibrary/astmp/original/original/c4/P4K.htm. The Army projection is that high average power travelling wave tubes and advanced RF weapons will be available by the year 2003. And by the year 2012, advanced conventional source systems and alternate source weapon systems are seen to be likely.

91. Naval Studies Board, 184-187, pp. 195-203.

92. USAF Scientific Advisory Board, pp. 27-29, 35-35.

93. USAF Scientific Advisory Board, pp. 22-26, 32-42.

94. Adapted from briefing material provided by Mr. Mike Diekhoff of a briefing given by Barry Hogge, Chief Scientist, Directed Energy Directorate, Phillips Research Site, “Assessment of the SAB Aerospace Expeditionary Force Studies Recommendations,” May 1, 1998.

95. Naval Studies Board, pp. 202-203.

96. Naval Studies Board, pp. 184-185.

97. USAF Scientific Advisory Board, pp. 36-38, 67.

98. Gen (ret) Ronald Fogelman, “Directed Energy-Applications in Tactical Airborne Combat, Phase One Results,” Address to the Directed Energy Symposium, Kirtland Air Force Base, NM, November 5, 1998.

99. Even a signal originating from a highly directional antenna will spread as a square of the distance.

100. Author interview, Patrick Vail, Air Force Research Laboratory, Phillips Research Site, November 6, 1998.

101. These effects were described in note 79 above. A broader discussion is available in Sowder, *et al*.

102. RF transmitting materials, such as epoxy/fiberglass, ceramic and fiberized ceramics, generally serve as good thermal insulators. Similarly, the material used for infrared seeker windows, such as gallium arsenide, quartz, diamonds, fiberized composites, are also generally thermally resistant. The destruction of the radome will likely dissipate much of the energy. See Cook, slide 11.

103. The Mid-Infrared Advanced Chemical Laser (MIRACL) has successfully engaged five BQM-34 sub-sonic drones as well as a supersonic Vandal missile target. The Airborne Laser Laboratory enjoyed similar success against drones and AIM-9 missiles.

More recently, the US-Israeli Nautilus Program used the MIRACL to successfully destroy a short-range rocket in-flight. While the flight parameters of the latter were substantially different from those encountered in the cruise missile regime, the destructive power of the laser was again demonstrated. See "Mid-Infrared Advanced Chemical Laser," *FAS Space Policy Project*, March 21, 1998, August 27, 1998, http://www.fas.org/spp/military/program/asat/miracl.htm. "Nautilus—Lasers Are Lethal," U.S. Army Space and Missile Defense Command, October 1997, October 31, 1998, http://www.smdc.army.mil/NAUT.HTML. "Tactical High Energy Laser (THEL) 21st Century Air Defense," U.S. Army Space and Missile Defense Command, October 31, 1998, http://www.smdc.army.mil/THEL.HTML.

104. See Cook, slide 11.

105. The assumption is that the laser system employs a phased array of laser diodes which do need to be trained or elevated prior to engagement. In fact, tests with the Sea Lite Beam Director demonstrated that while capable of rapid engagements, there remains a finite amount of time needed to shift from one target to the next. *See New World Vistas*, p. 67.

106. The SPS-48E is a three-dimensional air surveillance radar used as the primary organic sensor for the CVN's combat systems suite. Current plans call for the integration of the SPS-48E with other elements of the ship's anti-ship missile defense systems into a networked Ship's Self-Defense System (SSDS). The limiting factor for data updates remains the mechanical rotation in azimuth of the electronically scanned array. While plans call for passive sensors to provide 360-degree coverage, electronic surveillance systems are dependent upon one's opponent to radiate and electro-optical sensors are sensitive to environmental factors. See Martin Streetly, ed. *Jane's Radar and Electronic Warfare Systems 1997-1998* (London, UK: Jane's Information Group, Ltd. 1998), pp. 170-171.

107. Military helicopters pose a slightly different problem. Since they are generally turbine powered, they may present a significant IR source, if IRCM are not employed. They also tend to produce a broad spectrum of Doppler returns due to radar reflections from the blades. Nevertheless, their relatively low speeds, combined with the absence of a strong Doppler return, makes them a challenging target for conventional defense systems.

108. The *Saratoga* (CV 60) accidentally fired a salvo of two *Seasparrow* missiles at the Turkish destroyer, *Mauvenet*, on October 1, 1992. One of the two missiles, with a nominal 38-kg warhead, struck the ship. While the *Mauvenet* was not sunk, the bridge was destroyed and five crewmembers, including the captain, were killed. This damage equated to a "mission kill." See "The Navy's Year in Review," U. S. Naval Institute *Proceedings* 119, No. 5 (May 1993), p. 125.

109. "Facts and Figures," *Sea Power* 41, No. 1 (January 1998), p. 198.

110. CVN's typically employ a mix of 50 caliber machine guns and M-60's to deliver harassing fire. Even the 25mm chain gun, employed on other high value units such as fast combat support ships, has a limited range and effectiveness.

111. Without careful metallurgical inspection it may not be possible for an opponent to determine the reason for the hole in the waveguide. To the operator, the first symptom will likely be a system overload due to excessive reflected power. The potential subtleties of such an attack mechanism will make its incorporation into the rules of engagement challenging. Nor is it obvious whether this is more or less escalatory than active jamming.

112. In 1990, the U.K. Ministry of Defense acknowledged that it had developed and fielded a laser dazzle system, manufactured by Irwin Desman Ltd., for use by the Royal Navy's *Broadsword* frigates and *Type-42* destroyers. Although reported deployed to the Arabian Gulf for anti-small boat defense, industry sources assess it as capable of deterring a kamikaze style air attack. The system reportedly uses a low-power blue laser that does not cause permanent eye injuries. At a nominal range of 2.75 kilometers, an UWB microwave system would not only appear to be more effective, it would also preclude any concerns with violations of Protocol IV to the United Nations Conventions on Prohibitions on Conventional Weapons. A. P. O'Leary, ed. *Jane's Electro-optic Systems 1997-1998* (London, UK: Jane's Information Group, Ltd. 1998), pp. 11, 31-31.

113. The danger of fratricide in a counter-periscope mode would likely require that the laser weapon is controlled by an operator who makes the decision to engage. As competent submariners leave their periscopes exposed for only seconds, it is unlikely that there would be sufficient time for an operator to identify and engage a periscope target.

114. Such actions against legitimate collection platforms would have to be consistent with international protocols that permit the observation and collection of missile launch telemetry data.

115. *Nimitz* class CVN's have undergone steady combat system upgrades throughout their service lives. Current plans call for the incorporation of the Advanced Combat Direction System Block 1, the Advanced Integrated Electronic Warfare System, the Cooperative Engagement Capability, and the Mark 1 Ship's Self-Defense System. Department of the Navy, *Vision, Presence, Power—A Program Guide to the U.S. Navy 1998 Edition* (Washington, DC: Chief of Naval Operations, May 1998), pp. 59, 70-90.

116. Dennis J. Carroll, "Missile systems and naval operations 2010 and beyond," *Global Defence Review*, November 24, 1998, http://www.global-defence.com.

117. The Mark 15 Phalanx Close-in-Weapon System (CIWS) has a nominal weight of 13,600 pounds for the topside weapon assembly and an additional 725 pounds of below deck equipment. This equates to the weight and volume estimates for the Naval Research Laboratory's design for a 100 kW class shipboard laser. See "Facts and Figures," *Sea Power* 41, No. 1 (January 1998), p. 198.

118. *Nimitz*, the first CVN programmed to receive the Rolling Airframe Missile system, is scheduled for upgrade during its current re-fueling overhaul. There are presently two variants of the RIM-116A, the Block 0, which relies on passive RF for mid-course guidance and passive IR for terminal homing, and the new Block 1, which incorporates an infrared image-scanning seeker that permits autonomous infrared tracking of a non-emitting target. See “Raytheon Awarded $28 Million for Rolling Airframe Missile Work,” *Raytheon Press Release*, June 23, 1998, December 11, 1998, http://www.seiscor.com/pres/1998/jun/ramcon.html.

119. Each NATO *Seasparrow* Missile System (NSSMS) launcher assembly has a magazine of eight missiles. With three NSSMS launchers, the CVN can have up to 24 missiles loaded. Re-load of the NSSMS launcher is a lengthy (1 hour plus) process. Designed to replace both the NSSMS and CIWS, the RAM has a 21 missile magazine launcher. Three RAM systems would provide an additional 39 missiles above the 24 currently available in the three NSSMS magazine launchers. See Captain Richard Sharpe, OBE, RN, ed. *Jane’s Fighting Ships 1997-1998* (London, UK: Jane’s Information Group, Ltd. 1998), p. 802.

120. The configuration described is essentially the same as the Sea Lite Beam Director employed during its successful engagements.

121. The Royal Navy’s experience in the Falkland’s conflict illustrated that the actual expenditures of weapons far exceeded the models used to analytically calculate what would be necessary to neutralize the threat. As the British White Paper on the Falklands emphasized, the “rates of usage, particularly of ammunition, missiles and anti-submarine weapons were higher than anticipated.” Cordesman and Wagner quoted the White Paper in *The Lessons of Modern War*, and went on to generalize the same conclusion for all conflicts discussed in the series (1973 Arab-Israeli War, Iran-Iraq War, Falklands and Afghan conflicts) with the exception of the mujahideen who never had sufficient resources. See *The Falklands Campaign The Lessons* (London UK: HMSO, December 1982), p. 25, and Anthony H. Cordesman and Abraham R. Wagner, *The Lessons of Modern War*, Vol. 3, *The Afghan and Falklands Conflict* (Boulder, CO: Westview Press, 1990), pp. 330, 366.

122. Although there will probably be more missiles to re-load during any given evolution, the smaller size (9.2 ft vs. 12 ft) and the lighter weight (approximately one third the weight of the RIM-7) should facilitate the loading process. See *Sea Power*, pp. 196, 198. Any steps that reduce the requirements for handling conventional weapons dramatically simplifies the defense when chemical or biological weapons have been employed. The re-loading of mechanical gun systems (i.e., Mark 15 CIWS) is particularly challenging for personnel who are attired in full protective gear.

123. Adapted from Cook, slide 12. Data for UWB system developed from Sowders, et. al., and author interview with Patrick Vail, November 6, 1998.

124. Hughes, *Fleet Tactics*, p. 109.

125. *Naval Warfare*, p. 33.

126. While officially embracing the tenets of maneuver warfare as the superior form of naval warfare, NDP 1 acknowledges the historic role of the Battle of the Atlantic in World War II and other critical attrition warfare campaigns. Rather than attempting to force naval warfare into a template devised for land combat, Hughes argues that naval warfare is so distinct that it is best described as “power warfare.” His argument centers on the combatant units of naval forces and the typical outcomes of naval combat. Unlike actions ashore, classical naval combat results in the sinking or total elimination of the combat potential of one participant’s vessels. Crippled ships are typically not combat capable for months or years. The relatively small number of major combatants and the inherently high stakes of naval engagements result in a significantly different calculus for naval commanders. Captain Wayne P. Hughes, Jr. U.S. Navy (retired), “Naval Maneuver Warfare,” *Naval War College Review*, No. 3 (Summer 1997), p. 26. The next generation of shipboard weaponry, such as the French *ASTER*, the *Evolved Seasparrow*, and the Ship’s Self-Defense System, are all based upon the same principles of layered defense. See “Defence Power - Developments of the Decade,” *Global Defence Review*, http://www.global-defence.com; and Dennis J. Carroll, “Missile Systems and Naval Operations, 2010 and beyond.”

127. Boyd is probably most famous for his observation, orientation, decision, and action (OODA) loop. Introduced in the mid-1970’s it resonated with many who sought a shift to a more dynamic form of warfare. His concepts closely paralleled those of J. S. Lawson of the Naval Postgraduate School who developed a similar feedback model of the command and control-cycle that included five steps, “sense, process, compare, decide and act.” Hughes expanded Lawson’s concept by positing two interlocking loops defining the principal adversaries. Hughes, *Fleet Tactics*, pp. 175-189.

128. The parallels of land and sea warfare were articulated by T. E. Lawrence, the practitioner of unconventional desert warfare, who wrote, “In character our operations of development for the final stroke should be like naval warfare, in mobility, ubiquity, independence of bases and communications, ignoring of ground features, of strategic areas, of fixed directions, of fixed points.” See T. E. Lawrence, *Seven Pillars of Wisdom: A Triumph* (Garden City, NY. Doubleday, 1935), p. 337.

129. Boyd’s message can be summarized in his statement, “He who is willing and able to take the initiative to exploit variety, rapidity, and harmony - as basis to create as well as adapt to the more indistinct - more irregular - quicker changes of rhythm and pattern, yet shape focus and direction of effort - survives and dominates - or contrariwise - He who is unwilling or unable to take the initiative to exploit variety, rapidity, and harmony . . . goes under or survives to be dominated.” See John R. Boyd, “A Discourse on Winning and Losing” (Briefing materials, August 1987), p. 174.

130. The traditional Mahanian view was to mass the fleet in order to confront and destroy the opposing force and establish command of the sea. For Mahan, this conviction was so deeply held that he saw no justification in dividing the fleet. The depth of his conviction is reflected in his statement that if the Naval War College “had produced no other result than the profound realization by naval officers of the folly of dividing the battle-fleet, in peace or in war, it would by that alone have justified its existence and

paid its expenses." See *Naval Strategy: Compared and Contrasted with the Principles and Practice of Military Operations on Land* (Boston, MA: 1911), p. 6. Corbett took a more contemporary view, that by denying definitive combat, an opponent could continue to contest control of the seas in those areas where he might obtain a local superiority of forces. Corbett suggested that the contest for command of the sea might remain in dispute throughout a conflict. See Spenser Wilkinson, "Strategy in the Navy," *Morning Post* (London), 3 August 1909, November 24, 1998, http:www.mnsinc.com/cbassfrd/cwzhome/histart/wilkl.html.

131. During the early phase of the Solomon's campaign, Japanese destroyers, operating at night, without the benefit of radar, devastated U.S. cruisers by simply firing spreads of torpedoes along their track. The U.S. navy learned the lesson well and eight months later, Commander Frederick Moosebruger used a similar plan, developed by Commander Arleigh Burke, to sink three of four Japanese destroyers at the Battle of Vella Gulf. Burke's turn came in November 1943 when he had a similar success at the Battle of Cape Saint George. See E. B. Potter, *Sea Power—A Naval History*, Second Edition (Annapolis, MD: U.S. Naval Institute, 1981), p. 314. In 1917, the German Navy was able to demonstrate that small, relatively fast light craft were able to exploit the long nights at higher latitudes in order to destroy convoys and return safely to bases 500 nautical miles distant. See Bernard Brodie, *Sea Power in the Machine Age* (1943, reprint, New York, NY: Greenwood Press, 1969), p. 94.

132. Brodie, p. 94.

133. In *Fleet Tactics*, Hughes quotes LCDR McKearney's 1985 Naval Postgraduate School thesis which computed the overall probability of a torpedo hit by Japanese forces during the Solomon's campaign as being 0.06 with occasional battles, such as, Tassafaronga, reaching as high as 0.20. See Lieutenant Commander T. J. McKearney, USN, "The Solomons Naval Campaign: A Paradigm for Surface Warships in Maritime Strategy," Thesis, U.S. Naval Postgraduate School, Monterey, CA, 1985. In the example given, an attacker firing 16 SS-N-22 missiles would accomplish his mission if he could match the Japanese Navy's 0.06 success rate.

134. The term "fleet tactics" is taken from Captain Wayne P. Hughes' classic work of the same name. Hughes defines fleet tactics as dealing "with operations involving coordination between multiple ships and aircraft." He goes on to describe fleet tactics as the analog of grand tactics or operational art as the latter terms are used in land combat.

135. During the Gulf War, the threat of amphibious operations was used as a diversion; however, the mine problem highlighted the need for alternatives with greater flexibility and less predictability. See General Sir Peter de la Billiere, *Storm Command—A Personal Account of the Gulf War* (London, UK: Harper Collins Publishers, 1992), p. 148.

136. See *Concepts and Issues '98—Building A Corps for the 21st Century*, pp. 21-23.

137. The practical implications of Operational Maneuver From The Sea are well-articulated in Lieutenant Mark W. Beddoes, USN, “Logistical Implications of Operational Maneuver from the Sea” *Naval War College Review,* Autumn 1997, November 19, 1998, http://www.nwc.navy.mil/press/Review/1997/autumn/art3-a97.htm.

138. Hughes, *Fleet Tactics,* p. 250.

139. The Royal Navy encountered this problem during the Falkland’s conflict when two Exocet missiles fired at HMS *Ambuscade* were successfully deflected. After passing through a chaff cloud, they acquired and struck the *Atlantic Conveyor*. See Admiral Sandy Woodward and Patrick Robinson, *One Hundred Days* (London, UK: Harper Collins, 1992), p. 295.

140. The greater the distance from the enemy’s coast, the more time for the U.S. Navy to react. Only the major naval powers have vessels with the ability to operate at maximum speeds for extended periods and then to replenish without returning to port. The coastal patrol craft of many navies will be constrained by fuel if they undertake combat at distances of 100 nautical miles or more from a friendly port. Extended distances from land minimize the threats from land-based missiles and helicopters as well as that posed by tactical aviation.

141. For an elaboration of this discussion see Lieutenant Commander Charles C. Swicker, USN, “Ballistic Missile Defense from the Sea—The Commander’s Perspective” *Naval War College Review*, Spring 1997, November 19, 1998, http://www.nwc.navy.mil/press/Review/1997/spring/art1sp97.htm.

142. Geoffrey Till reminds readers of Sir Julian Corbett’s words, “This power of disturbing the enemy with feints is of course inherent in the peculiar attributes of combined operations: in minesweeping vessels, for instance, there is a new instrument . . . capable of creating a very strong impression at a small cost to the fleet. Should a flotilla of such craft appear at any practicable part of a threatened coast and make a show of clearing it, it will almost be a moral impossibility to ignore the demonstration.” See *Some Principles of Maritime Strategy*, J. S. Corbett, ed. E. J. Grove (London: Brassey’s, 1988), p. 303. Geoffrey Till, “Corbett and the 1990’s,” *Mahan is Not Enough—The Proceedings of a Conference on the Works of Sir Julian Corbett and Admiral Sir Herbert Richmond,* ed. James Goldrick and John B. Hattendorf (Newport, RI: Naval War College Press, 1993), p. 224.

143. The minimum weather conditions needed to support visual flight operations is likely to be roughly sufficient for the employment of the HEL and its sensors.

144. The HEL also may have significant utility during replenishment operations. Unlike other defensive systems, it can be employed without undue hazard during refueling and ordnance handling evolutions.

145. While Naval aviators have long aspired to achieve this goal, the limitations of both offensive and defensive systems previously made it impractical. Hughes summarizes the issues that confronted Nimitz during the Second World War and led to the adoption of the massed defense. See Hughes, *Fleet Tactics*, pp. 104-105.

146. Boyd, p. 174.

147. Designers seek to minimize heat dissipation requirements and power demands by operating at lower voltages; unfortunately, such an approach reduces the amount of energy needed to damage or disrupt the device. This is the inherent risk in adopting the commercial standard for military applications. The one positive development is the trend towards more fault tolerant architectures that incorporate automatic "soft resets" when disrupted.

148. Sowders, pp. 19-20.

149. There are limited data that suggest certain modulation patterns may increase the probability of disruption. Additional research is necessary before one can assess whether this can be exploited in the design of operational systems. See Sowders, et al.

150. Merritt, *op. cit*.

151. Sowders, p. 30.

152. Senator Tom Harkin (D-IA) has led the fight against the MIRACL testing in Congress calling it "both unnecessary and provocative." He is quoted by *Inside the Army* as saying, "The Congress, the White House and the Pentagon have to have a serious discussion of our nation's anti-satellite weapons plans before we go down the road of testing these weapons—although the Pentagon is spinning the tests as a way to measure U.S. satellite vulnerability, most arms control analysts would describe the test as a major step in developing an ASAT weapon. These are the same types of tests that I and others in Congress objected to years ago." *Inside the Army*, November 30, 1998, pp. 13-17. Quoted in *AFSPC Legislative Liaison*, December 10, 1998. Whether one agrees with the senator or not, his remarks make it evident that there are major unresolved national strategy issues regarding development of any anti-satellite capability.

153. *Los Angeles Times*, 28 November 1998, quoted in *AFSPC Legislative Liaison*, December 10, 1998.

154. Development of an embedded HPM feature as an adjunct capability in future high power radar systems may be a prudent investment; however, the fundamental susceptibility to countermeasures does not support independent development for ship self-defense applications.

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